WADC TECHNICAL REPORT 54-15

AN ENGINEERING STUDY OF FERROMAGNETIC STRUCTURES AND MATERIALS

D. E. BOVEY

GENERAL ELECTRIC COMPANY

APRIL 1954

WRIGHT AIR DEVELOPMENT CENTER

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FOREWORD

The engineering study of ferromagnetic structures and materials that is described in this report was conducted in the General Electric Engineering Laboratory of the General Electric Company on contract AF 33(616)-72, under the authority of Proj. C-3-006. It was sponsored by the Aero Medical Laboratory of the USAF, Wright Air Development Center at Wright-Patterson Air Force Base, Ohio with Mr. M. A. McLennan as technical advisor for the Aero Medical Laboratory.

The work was conducted in the Magnetic Equipment and Instrument Services Unit, under the supervision of Mr. W. D. Williams. The author of the report, Mr. D. E. Bovey was the project engineer. Mr. J. D. Young and Mr. W. A. Bryany actively participated in the investigation, as well as several others of the Laboratory personnel who assisted in the consulting service.

The preparation of this report completes the work to be done under the above contract.

ABSTRACT

Twenty-three specimens of the recently developed high quality magnetic materials, including ferrites and thin gage strip wound cores, were compared in preliminary tests by making dynamic hysteresis loops and core loss measurements. Wound cores of 0.002 inch Supermalloy tape were selected as being potentially the best for subminiature variable inductor cores. Inductors to be controlled with one microwatt of DC control power cannot be designed to have sufficiently high Q values for satisfactory use in tank circuits of oscillators. However, a new oscillator that can be controlled with the low Q inductors to secure frequency modulated carriers was developed, and is described. In a very limited series of tests the new oscillator was found to operate as desired at frequencies as high as 60 kilocycles. Magnetic design data and procedures for 0.002 inch Supermalloy in the frequency range from 500 cycles to one megacycle are included.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JACK BOLLERUD
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
Directorate of Research

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INTRODUCTION

A portion of the work of the Aero Medical Laboratory at the Wright-Patterson Air Force Base involves the measurement of various physiological and associated functions. The data thus secured may be transmitted from the points at which they are measured to a recording location by means of a suitable telemetering process. Several systems are being investigated.

In order to make possible the incorporation of the small size components that are required for the design of the cigarette package size transmitters required by one proposed system, the use of subminiature saturable inductors is indicated.

The object of the investigation herein described is to determine which magnetic materials are the most suitable for use in the cores of subminiature inductors; to secure data concerning the magnetic characteristics of these materials; and to develop methods for designing suitable subminiature inductors on the basis of the data secured.

SECTION I

SUMMARY

The various magnetic materials that were considered potentially useful for the cores of variable subminiature inductors were examined in preselection tests by comparing their dynamic hysteresis loops. These loops were made at 500 cycles and at 10 kilocycles, in most cases, although a few were made at frequencies up to 120 kilocycles. Photographs of 76 of these loops are included.

Magnetization and permeability curves of four of the most promising of the materials were made from the photographs of the hysteresis loops.

Preliminary measurements of core loss vs. peak AC flux density were made for about a dozen of the better materials at 500 cycles and at 10 kilocycles.

The most suitable core for the intended purpose was determined to be a torroidal one, tape wound, of 0.002" Supermalloy, enclosed in a standard Nylon case for mechanical protection. This core has an I. D. of 0.440", an O. D. of 0.810" and a height of 0.195", over-all. It weighs slightly less than four grams.

Inductors using this core can be made which are suitable for amplitude modulation telemetering systems, but the effective resistances are high, and the Q values low. They are not generally useful in L-C tuned circuits, such as the tank circuits of oscillators.

A new oscillator was constructed and tested which can be frequency controlled with one microwatt of DC control power by means of low Q inductors. This oscillator makes use of the inductor as a controllable resistor in an R-C circuit having a fixed capacitance.

The new oscillator, and a method of designing inductors using the data that are included, is described in detail.

The effects of transverse biasing fields on inductors of the type required were investigated, and it was determined that, although the effects of the earth's field were negligible, the inductors should be shielded from other fields that are much stronger.

The magnetizing forces resulting from normal operating currents do not produce troublesome effects due to residual magnetism, but the inductor cores should be demagnetized before calibration and use, and protected from magnetizing forces due to overloads or external fields.

Magnetic noise was found to be no problem.

The use of the new oscillator and the data and design procedures described will make possible the attainment of the major objective for which this investigation was originated; i.e., the design of variable subminiature inductors suitable for use in both amplitude and frequency modulated telemetering systems satisfactory for transmitting physiological data with very small units.

SECTION II

TECHNICAL PROCEDURE

A search of the technical literature revealed the fact that most of the magnetic amplifier work that has been done has been in connection with other frequencies or other applications than the one contemplated, and the results were not directly applicable to this investigation. A bibliography appears as a later section of this report.

Table 1 of the RESULTS section is a list of all the materials tested in this investigation. Specimens that were available as a result of previous work are included. In addition to those initially on hand, cores of other materials considered potentially useful were ordered, if they were found to be commercially available.

Duplication of materials of similar compositions and specifications manufactured by different producers under different trade names was avoided. In some cases, it was found that advertised materials could be secured only in quantities in certain gages. In such cases it is often necessary to wait many months for the rolling of the material and the fabrication of the cores to supply the individual orders. This is particularly true when gages thinner than 0.001" are involved.

Preliminary selection tests were made by producing dynamic hysteresis loops on the specimens by means of the test circuits described in Appendix A, Section I. These loops are included in the RESULTS section, as Figures 1 to 76, inclusive. They provided a rapid means for selecting specimens that appeared promising for further tests; for deriving AC magnetization and permeability curves; and for use in analyzing data taken by other test methods.

In the lower frequency ranges up to about ten kilocycles, and with some of the larger specimens which were on hand at the start of the project, the total core loss was measured by means of a light beam wattmeter, as described in Appendix A, Section II. As the investigation proceeded, it became clear that the materials would not be worked at high peak AC flux densities. Smaller specimens were secured for testing and the power measurements were then made by means of the vector method, described in Section III of Appendix A.

After some data had been secured on the cores that had originally been available and some of the subminiature ones that had been ordered were received, these were wound to produce subminiature inductors for tests. The inductances and impedances of these were measured, and the effects of transverse bias fields were also studied by means of the test setup described in Section IV of Appendix A.

The effects of residual magnetism in the cores was also determined by applying various DC and AC magnetizing forces to the cores and then repetitively increasing and descreasing the DC control field to different maximum values, and observing the relationship of inductor impedance to control current.

The response times of the inductors were checked by applying the maximum amount of control current to the control winding, and viewing the voltage drop across a resistor carrying the alternating load current. By simply counting the number of cycles from the time of application of the control current until the load current reached its steady state value, the response time could be determined. This procedure was accomplished when using a cathode-ray oscilloscope having a single triggered sweep of long duration. The effects of the impedances of the control and of the load circuits of the inductors were determined.

The data taken during the first half of the investigation were rather general in nature, and were intended to provide information that could be used in designing trial inductors that could actually be used for the purposes intended. These data proved that inductors could be designed that could be controlled with less than a microwatt of DC control power, and that such inductors could be designed in the sizes desired. However, these inductors, although applicable to telemetering applications involving amplitude modulation, did not appear to be suitable for use in tuned circuits because of the low values of Q, or quality factor, that were found to exist in all cases of inductors having adequate control characteristics.

A meeting was arranged, and Mr. M. A. McLennan, of the Aero Medical Laboratory supplied the additional information that it was desirable that a means of designing inductors for use in a frequency modulation system and using a commercially available core material, should be developed.

It was noted that in order to secure satisfactory operation in the tuned grid circuit of an oscillator to be used for producing a frequency modulated signal, it would be necessary to secure inductors with Q values of five or more. It was stated that the oscillators would involve the use of low conductance, subminiature vacuum tubes having mutual conductance values of not more than 600.

The various technical details of the entire investigation were considered, and it was agreed that attempts would be made to determine the design of reactors having Q values sufficiently high to permit satisfactory operation in tuned circuits.

The test data indicated that the 0.002" Supermalloy tape wound cores had the best combination of qualities required for the design of the desired inductors. Consequently, all effort was directed to attempts to use this material. Inductors were designed and tested, and it was found possible to make a Colpitts oscillator, using a low mutual conductance tube, operate at a frequency of about 1000 cycles per second. However, only a limited amount of control was secured because it was found to be necessary to apply a fixed bias to the core to increase the Q value to permit oscillation. The amount of control that could then be secured with one microwatt of control power was quite limited.

In a study of this problem, a technique was conceived that would permit the use of low Q inductors. The oscillator circuit shown and described in

Appendix B was tested. This was found to provide much better operation and control. Several modifications are shown.

With the discovery of the oscillator circuit of Appendix B, it became obvious that it was desirable to have more complete information about the thin gage Supermalloy core. Additional data were taken by the methods mentioned and described previously, and a design procedure was developed for designing low Q inductors suitable for use in this type of oscillator. This design procedure is described fully in Appendix C.

SECTION III

RESULTS

The results listed below were secured and will be discussed in some detail in the DISCUSSION OF RESULTS section.

1. Preliminary comparisons of magnetic characteristics of the materials listed in Table 1 were made.

Table 1

Tape Wound Cores	Solid Cores
0.001" Supermalloy	Ceramag 5N
0.002" Supermalloy	Ceramag 7
0.001" Monimax	Ceramag 8
0.002" Monimax	Ferramic G
0.003" Monimax	Ferramic H
0.010" Monimax	Ferramic 1118
0.001" Deltamax	Ferroxcube #3
0.002" 47-50 Alloy	Powdered Iron
0.010" 47-50 Alloy	Powdered Mo Permalloy
0.001" 4-79 Mo Permalloy	
0.002" SX-10	**Cut Cores**
0.010" Mu Metal	0.001" Silectron
0.006" Hy Mu 80	

2. Dynamic hysteresis loops (both symmetrical and nonsymmetrical) were made as parts of the preselection tests and are shown in Figures 1 to 76, inclusive.

3. Magnetization and permeability curves were made for some materials as part of the preselection tests and are shown as Figures 77 to 81, inclusive.

4. Core loss data at 500 c.p.s. and at 10 kc. were secured as part of the preselection tests and are shown in Figures 82 and 83.

5. The optimum core shape, construction and size for the intended application was determined.

6. The effects of transverse biasing fields were determined.

7. The effect of residual magnetism in the cores on the reproducibility of the inductor control characteristics was determined.

8. The response times of several inductors constructed with cores of some of the more promising materials were measured.

9. The results secured during the first half of the investigation were reviewed with Mr. J. A. McLennan from the Wright-Patterson Air Force Base, and the tentative program for the remainder of the investigation was discussed.

10. It was determined that inductors to be controlled with one microwatt of control power, and to have Q values of five or more, are not practical with core materials commercially available at the present time.

11. A wound core of Supermalloy tape, 0.002" thick and 1/8" wide, was selected as potentially the best commercially available core for the intended use.

12. Demonstration was made of the fact that limited frequency control of a Colpitts oscillator could be secured in the low frequency range with one microwatt of control power expended in an inductor having a subminiature wound core of 0.002" Supermalloy tape.

13. The oscillator described in Appendix B was tested and found to be operable as desired, with low Q subminiature inductors having Supermalloy cores.

14. Magnetic characteristics of the 0.002" Supermalloy tape wound core were measured and the data listed below are included as Figures 84 to 95, inclusive.

Figures 84 and 85 - 500 Cycle Impedance Characteristics vs. DC Control Field.

Figure 86 - Low Density Magnetization curves for 0.002" Supermalloy and Ferroxcube #3 at 10 kc. and 50 kc.

Figure 87 - Core Loss vs. Peak Flux Density curves from 500 cycles to 1 megacycle.

Figure 88 - Low Density Magnetization curves from 500 cycles to 1 megacycle - Rectangular Coordinates.

Figure 89 - Same as Figure 88 - Logarithmic Coordinates.

Figure 90 - Incremental Permeability vs. Peak Flux Density curves from 500 cycles to 1 megacycle with 0 DC bias.

Figure 91 - Incremental Permeability vs. Control DC Magnetizing Force - 10 kc.

Figure 92 - Incremental Permeability vs. Control DC Magnetizing Force - 50 kc.

Figure 93 - Incremental Permeability Variation vs. Control DC Magnetizing Force - 500 cycles to 100 kilocycles.

Figure 94 - Incremental Permeability Variation vs. Control DC Magnetizing Force - 10 kc.

Figure 95 - Incremental Permeability Variation vs. Control DC Magnetizing Force - 100 kc.

15. A procedure for designing inductors that would be suitable for use in an oscillator, such as listed in item 13, and using the design data listed in item 14, was developed and is described in Appendix C.

SECTION IV

DISCUSSION OF RESULTS

General

The engineers at the Aeromedical Center wish to measure and remotely record physiological data such as body and skin temperatures, pulse rates, blood pressures, skin resistances and respiration rates. The quantities to be measured would normally be converted to direct currents by means of strain gages, photoelectric cells, thermocouples or other very small pickup devices.

The direct currents from the pickup devices would then be supplied to a suitable telemetering system for transmission from the measurement location to a remote recording location. At the recording location the received signal would be indicated or recorded for a permanent record.

Although there are several possible telemetering systems available, it is most desirable that the one used include certain characteristics to be listed.

The size of a transmittor unit should be very small, preferably not larger than a cigarette package. This specification is dictated by the necessity of attaching the transmittor units to the bodies of men or animals being tested, without involving unnecessary bulk or weight. The construction of such small transmitting units requires the use of subminiature components.

A telemetering system using frequency modulation is preferable to one using amplitude modulation. This preference is based on the need to avoid certain technical difficulties such as fluctuating voltage sources, variable components, electrical noise and other items that cannot be easily controlled.

Transmission by radio is also preferred to avoid the necessity for connecting or trailing wires. The transmission distances that will be involved are short, and frequency modulated radio has been found to be quite satisfactory for actual transmission.

The DC control power that will be available from the pickup unit and which must be used to accomplish modulation of the carrier wave, will ordinarily be limited to a maximum of one microwatt.

Carrier frequencies that have been commonly used in telemetering work range from about 1000 cycles per second to 150 kilocycles. These carriers are ordinarily modulated about plus or minus 7-1/2% of the carrier frequency. In some cases, all of the modulation is above or all is below the carrier frequency. Occasionally, a total frequency variation of as low as 5% can be used.

These frequency specifications indicate that if an oscillator frequency was controlled by a variation of the inductance in an LC circuit, the inductance

variation would have to be about 30%. In the proposed application, the 30% variation of inductance would have to be secured with the 1 microwatt of DC control power.

It was hoped that it would be possible to use subminiature inductors in this manner and modulate an oscillator frequency, which would in turn drive a very small power amplifier having an output of approximately four milliwatts. The power from the amplifier would be radiated from an antenna worn by the subject and the radiated energy would be picked up by a large loop located near the subject.

To assure successful operation with the subminiature vacuum tubes that would be used in this type of oscillator, the parallel resonant impedance of the LC circuit should be at least 5000 ohms. The Q of the inductor in this circuit should, of course, be as high as possible, but it was thought that satisfactory operation could be secured if the Q were as low as five. It was expected that subminiature vacuum tubes having mutual conductances not greater than 600 would probably have to be used.

It would not be important to have similar inductances identical to each other since each oscillator would be separately calibrated and compensated. However, it would be important to have accurate repetition of oscillator frequency with respect to control current in the case of each oscillator.

A careful consideration of the requirements listed above indicates that many factors are involved in the design of controllable inductors that would be satisfactory in all respects for the proposed application. For the sake of clarity, several of the most important factors will be discussed separately.

The most severe limitation involved in designing suitable inductors for the proposed application is the combination of requirements of small size, practically obtainable values of Q, or quality factor, and the limited amount of DC control power that will be available. It was determined that on any core that might be suitable for use, the maximum DC magnetizing force that could be produced with 1 microwatt of control power was not more than about .06 oersteds, which is equivalent to about 0.05 ampere turns per centimeter. It was found, also, that this figure could not be increased to any extent by changing the size of the core by making it either larger or smaller. It is obvious that a "high permeability" material must be used in order to secure sufficient control with the small amount of control power that is available.

A remote tuning radio receiver having no moving parts was described by Mr. Samuel Steiber, of the Signal Corps Engineering Labs., Fort Monmouth, N. J., in a paper delivered at the 1952 National Electronics Conference at Chicago. Controllable inductors were used in tuned circuits in this receiver. The inductance variations secured were much greater than those required in the proposed application, but the DC control power required was many thousand times greater than permitted by the limitations existing in this application. Ferrite cores were used, but because of the comparatively large amount of control power required, it has been found that these materials are not suitable for the work which is the subject of this investigation.

Initial considerations of the problem indicated that there were a number of "high permeability" materials that should be considered. "High permeability" is a relative term and some high permeability materials have much higher permeabilities than others. The thin gage strip materials initially considered were the following: Monimax, Deltamax, Sinimax, 47-50 Alloy, Supermalloy, 4-79 Mo Permalloy, Mumetal, SX-10, Permalloy, 45 Permalloy, 65 Permalloy, Hypernik, Hypercore, Hypersil, Orthonik and Purified Iron. Some of the materials in this list are similar to each other, since they are made by different companies under different trade names, but have essentially the same compositions and treatments. For example, Orthonik, Hypernik and Deltamax are similar. Hypersil and SX-10 are similar. Since some of these materials are not commercially available, the list in Table 1 was prepared to be representative of the commercially available materials that should be included in the preliminary selection tests. It was also considered desirable to include ferrites made by various manufacturers and some of the cores made from powdered iron, so these were also included.

The ideal core material for use in an inductor to be incorporated in the frequency determining networks of an oscillator would be one that would permit the design of a very small inductor having a very high Q, a high inductance with a few turns and a large variation of inductance with very very small amounts of control power. Such a material would need to have very low losses and high initial AC permeability, which would change rapidly with extremely small amounts of DC bias. For example, a material that had the initial AC permeability characteristics of the ferrites, the low density DC permeability of Supermalloy, less losses than either the ferrites or Supermalloy and the characteristic that the AC permeability would be rapidly altered by a very small change of DC bias, would be ideal. Unfortunately, no such material is commercially available at the present time. With the large amount of effort being applied to metallurgical research in many laboratories, it is hoped that a material more closely approaching the right combination of these characteristics will be developed within a reasonable time.

The results secured in this investigation will now be considered as they apply to the factors discussed above.

Dynamic Hysteresis Loops

The technique used in the production of these loops is described in Appendix A, Section I.

In the first phases of the investigation, it was realized that some materials that might be useful at the lower frequencies would probably have high frequency losses that would limit their usefulness to the low frequency range. For this reason, ten kilocycles was chosen for the first preselection tests. The dynamic hysteresis loops of a number of specimens were produced and photographed, and are shown in Figures 7 to 25, inclusive.

In these loops, the area is directly proportional to the total core loss per cycle in the specimen, and the X intercepts are proportional to the AC coercive force. The maximum magnetizing force and the maximum flux density can be read directly, so the AC magnetization curve for a specimen can be derived from a series of loops made at the same frequency and scale, but at different peak magnetizing forces.

Figures 7 and 8 are alike, except that a higher peak magnetizing force was used in the case of the latter. A comparison of Figures 8, 9 and 14 shows that at 10 kilocycles the total core losses increase rapidly with lamination thickness. It is desirable to use thin laminations at the higher frequencies. Comparison of Figures 7 to 25 shows that the 0.001" Supermalloy has the lowest loss, the 0.001" 4-79 Mo-Permalloy is next and it is followed by the ferrites and other materials. It seems that of the materials shown, the 0.001" Deltamax probably has the highest loss that can be tolerated.

Figures 26 to 36, inclusive, show the 500 cycle loops of several of the materials. It will be observed that the one, two and three mil thicknesses of Monimax show very small variations, but the loss in the ten mil thickness is much greater at five hundred cycles than that in the thinner gages. The one mil Deltamax is about the same as the three thin gages of Monimax. The one mil Supermalloy and the one mil 4-79 Mo-Permalloy both have relatively low losses at five hundred cycles.

On the basis of losses in the frequency range up to ten kilocycles, the thin gage Supermalloy was the best material tested, although its saturation density was lower than for some of the others.

Figures 37 to 41, inclusive, show how the dynamic loops are used for the derivation of AC magnetization curves. In each of Figures 37 to 40, a series of exposures was made for each of several different peak flux densities. The locus of the tips of the individual loops is the AC magnetization curve. It is a simple matter to read the values of the coordinates of various points on the magnetization curves so these can be plotted on graph paper to any selected scale.

Figure 40 shows a series of 100 kilocycle loops for the same specimen as was used for Figure 39. Comparison of these two Figures shows that both the

10 and 100 kilocycle loops and magnetization curves are the same. This result is consistent with previous data that had been taken, which had shown that the core loss in this specimen was directly proportional to the frequency, when a constant peak flux density was maintained. This fact can only be true if the loss per cycle is constant with frequency variation. When the loss per cycle is constant, the areas of the dynamic loops must all be the same at the same peak flux density at each frequency.

Figure 41 shows an AC magnetization curve produced by adjusting the oscilloscope so the tip of the dynamic loop has the greatest intensity, and then continuously varying the magnetizing force from zero to maximum with the lens of the oscilloscope camera left open for a long exposure.

The 500 cycle magnetization and permeability curves of Figures 77 to 80, inclusive, were made from the dynamic hysteresis loops shown in Figures 37, 38, and 42 to 62, inclusive. Figure 81 includes the magnetization curves of Figures 77 to 80, and that of Ferroxcube #3 for comparison.

The effect of the DC bias field on the AC permeability of a core material was investigated for both low and high density AC fields. In figure 63, a constant 500 cycle peak flux density of 400 gausses was maintained in a specimen of one mil Deltamax, while the DC bias magnetizing force was varied from 0 to 0.37 ampere turns per centimeter. The incremental permeability is a maximum at zero bias, and continually decreases as the DC bias is increased. The incremental permeability is determined from the slope of a straight line drawn through the tips of the minor loop. This method of measuring incremental permeability is particularly useful, for rapid comparisons, and for the study of the effects of different variables on the incremental permeability.

Figures 64 to 76, inclusive, show the effects of DC bias on incremental permeability for high AC flux densities.

The correlation between incremental permeability and inductance is rather indefinite when high AC flux densities are involved in which the peak flux density is on or over the knee of the magnetization curve. The reason for this is that in such cases the magnetizing current contains large harmonics, and a single frequency is no longer involved.

The impedance of an inductor of this type is not easily correlated with the incremental permeability, since the additional factor of high effective resistance is included, and this also varies with bias.

The production of dynamic hysteresis loops provides a rapid, economical and convenient method of graphically comparing magnetic materials and of determining AC magnetization and permeability curves.

Core Loss and Quality Factor, Q

The core loss in a material for use in a subminiature inductor of the type under consideration is significant because of its influence on the effective

resistance and the quality factor, Q, of the inductor. The value Q for an inductor is the quotient of its inductive reactance divided by its effective resistance.

The effective resistance of an inductor is the quotient of its power loss in watts, divided by the square of the effective value of its exciting current.

In telemetering applications it would be unusual for such inductors to be designed for operation at flux densities high enough for the matter of heat dissipation to be important. The high effective resistance and the resulting low value of Q is the limiting factor in the determination of the maximum permissible core loss of a material for use in such inductor cores.

Most inductors used at audio or radio frequencies are designed so the resistance of the winding is the limiting factor in attaining a high value of Q. The core usually includes at least a small air gap, so its effective permeability is relatively low. (In some inductors having no air gaps, relatively low permeability core materials are used.) For this reason the exciting current is relatively large, and the contribution of the core loss to the effective resistance is made small in comparison with that of the winding.

In the present application the attainment of a high Q inductor by means of the simple expedient of including an air gap, or of using a material of low AC permeability, is not possible. The DC control power available is not sufficient to alter the AC permeabilities by a sufficient amount in materials having low AC permeabilities. For example, the use of a ferrite, Ferroxcube #3, made possible the construction of an inductor having sufficient Q, but it was necessary to use at least two microwatts of control power to secure a measurable change of inductance, and in order to secure a large enough change, it was necessary to use about 30 microwatts.

It would not be important if the permeability of the core were exceptionally high, if the core loss were zero (but unfortunately, such material does not exist). For example, if two cores had equal permeabilities, but one had only half the loss of the other (under the same operating conditions), the Q of an inductor wound on the low loss core would be twice as great as that for an identical inductor using the other core. This results from the fact that the exciting current and inductive reactance of each inductor would be the same, but the effective resistance of the one having the low loss core would be only half as much as for the other one. Thus, two materials should be equally good if the one having the highest permeability had losses proportionately lower than the other, while still possessing the other required characteristics.

By way of comparison, Figure 86 shows the 10 and the 50 kilocycle magnetization curves for Ferroxcube #3 ferrite, and the 10 and 50 kilocycle magnetization curves of the 0.002" Supermalloy. It will be noted that the 10 kilocycle permeability of the Ferroxcube #3 at 500 gausses is about 1000, while that of the Supermalloy at the same density is about 23,000. The ratio is approximately 23:1. However, the ratio of core loss in a Ferroxcube #3 core to the core loss in a 0.002" Supermalloy core of the same physical size, is much less than 23:1

at 500 gausses and 10 kilocycles. This means that at this frequency and flux density, an inductor using the Ferroxcube core would have a higher Q than one using the Supermalloy core. Unfortunately, however, as has been pointed out before, the use of a Ferroxcube core will not permit the amount of control that is required.

It is desirable to use an inductance having as high a Q as possible in the tank circuit of an oscillator, in order to secure frequency stability and consistent oscillation. Inductances having low Q values have very broad resonance curves, and L-C oscillators incorporating such inductors do not operate in a satisfactory manner.

It was concluded that on the basis of the facts discussed, the thin gage Supermalloy was the material that had the best possibilities for use in cores for subminiature controllable inductors. It was also concluded, however, that such inductors having sufficient high values of Q could only be designed for operation in limited portions of the desired frequency range.

Coincidental with the consideration of this problem, the oscillator described in Appendix B was conceived and tested. It was found that low Q inductors could be successfully used in this circuit. There was not a sufficient amount of time to conduct more than a preliminary investigation of the possibilities of this oscillator, but enough tests were made to show that it could be used over a much wider frequency range than that of the L-C oscillator.

It was, therefore, decided that a complete set of data on the characteristics of the two mil Supermalloy core should be included, even though it was known that the design of high Q controllable inductors would be impossible with this material. The core loss data of Figure 87 were included as a necessary portion of the information required to design inductors for the oscillator described in Appendix B.

Core Construction

Several types of core construction were initially considered, which included tape wound ring cores, or "toroids"; cores made from punched laminations; and "cut" cores, made by winding the core material tape with a suitable binder to make a mechanically solid core, and then cutting this in two to form two "C" sections which could be clamped, or otherwise held together, after the windings had been put in place.

During the progress of the test, it was determined that since it would be necessary to use very thin laminations in order to reduce core losses at the higher frequencies, the punched cores could not be considered. It has been found impractical by core manufacturers to punch laminations thinner than .003", and the core manufacturers do not wish to punch laminations of the high quality nickel iron alloys in any thicknesses.

The cut, or "C" cores, are not practical for this application because they do include a very small air gap. It is obvious that if a total air gap of .001"

is included in a core of material having a permeability of 50,000, this air gap is equivalent to a magnetic circuit length of 50" of the core material. Since the total length of the magnetic circuit of a suitable core would be in the order of 2", it is obvious that even a small air gap cannot be permitted, since it would eliminate the possibility of securing adequate DC control. A small cut core made of .003" Silectron was tested and it was found impossible to secure any control at all with one microwatt of control power.

For these reasons, it became obvious that a wound core of thin, high permeability material would be most suitable. The size #5340, made by the Arnold Engineering Company, of Marengo, Illinois, was found to be the most practical. The dimensions of this core are I. D. .500", O. D. .750" and H 0.125". This size of core can be made of thin gage Supermalloy, Deltamax, 4-79 Mo Permalloy and other materials.

The high quality materials are quite strain sensitive, so each of these cores is encased in a standard Nylon container having the dimensions I. D. 0.440", O. D. 0.810" and H 0.195".

Since the cost of a high quality core this size is composed mostly of labor costs, the prices of these cores are substantially independent of the core material used, but the thinnest gages are the most expensive. It is not recommended that a gage thicker than 0.003" should be considered.

It was determined experimentally that if an AC winding with sufficient turns of small enamel insulated copper wire were placed on the #5340 size core, and the remaining space was completely filled with a control winding of larger copper wire, it was impossible to secure more than 0.05 ampere turns per centimeter of DC bias magnetizing force with one microwatt of control power. The AC winding was composed of 1000 turns of 0.005" Heavy Formex insulated copper wire, and the control winding of 44 turns of #18 H. F. copper wire. Increasing or decreasing the size of the core did not increase the amount of DC bias that could be secured with one microwatt of control power. If fewer turns were required in the AC winding, slightly more space would be left for the control winding, but the difference is not appreciable. The size of wire used in the control winding is not critical, but sizes larger than #18 are difficult to handle, mechanically, on this core, and smaller sizes have poorer space factors.

The size #5340 cores of thin tape wound material weigh between three and four grams, each, depending on the material used.

It will be noted that for a fixed lamination thickness with a specific material, the quality factor of the core is determined by the frequency and flux density, and is independent of the volume of the core, and is independent of the disposition of magnetic material.

Residual Magnetism Effects

One of the important requirements of inductors to be used in telemetering work is repetitive accuracy. For any specific inductor it is important that a

particular variation, or sequence of variations of control field will always produce the same variations of inductance and impedance of the inductor. Since each inductor would be separately calibrated and compensated in the proposed application, uniformity between units is not required. However, in the case of inductors using two cores with separate AC windings and single control windings, it is important for the cores to be matched. Also, matching is required when two inductors are used with the AC windings in series, aiding, and the control windings in series, opposing, to eliminate transformer action between the AC and control windings.

Residual magnetism must be controlled in order to secure matching, or repetitive accuracy. It was determined that if a core was demagnetized and then protected from external fields, the magnetizing forces produced by a few microwatts of control power were not sufficient to produce enough residual magnetism in the core to cause trouble. No difficulty was experienced as a result of the effects of the normal AC in its winding.

Demagnetizing the core is not difficult, and can be done in a standard demagnetizer, either before winding, with the windings in place, or probably with the inductor in place in an item of equipment, if there are no components that would be damaged by a strong AC magnetic field at 60 cycles.

Figure 91 shows the results secured when a constant peak flux density of 500 gausses at 10 kilocycles was maintained, while the control DC magnetizing force was repeatedly varied between the limits of zero and 0.08 ampere turns per centimeter, which represents a power expenditure of over two microwatts in the control winding. The solid curve represents the average readings, while the dotted ones include all points read. It will be noted that the extremes of deviation were not more than plus or minus 5% of the true values. This accuracy is comparable to that of the instruments used in making the tests, so it is probable that the deviations represent experimental error.

It was concluded that no difficulties should be experienced as a result of residual magnetism if reasonable precautions were taken to demagnetize the cores before calibration and to protect them from the influence of strong magnetic fields after demagnetization.

Transverse Biasing Fields

The effects of transverse biasing fields were investigated by means of the test setup described in Appendix A, Section IV.

It was determined that if a truly transverse field could be applied to the ring cores that were adopted as being the most suitable, the effect was negligible. If the transverse field was strong and not completely transverse, or if it was not uniform, there would be a component of magnetizing force in such a direction that it would alter the control field and produce an unwanted variation of inductor impedance.

The earth's field was found to be too weak to affect these inductors.

Magnetic fields as strong as 700 oersteds were used in this investigation.

It was concluded that no advantages could be secured by attempting to use transverse fields for control, but that weak fields, such as that of the earth, would not cause difficulty. Since other fields that might exist in the vicinity of the equipment incorporating the subminiature inductors would undoubtedly be non-uniform, and have components in a direction to influence the control of the inductor, it should be shielded from any strong fields.

Response Time

In order to accurately record rapidly changing functions, it is necessary that impedance changes of the inductor follow control field changes rapidly.

Response time tests were made on cores of one mil Deltamax, one mil 4-79 Mo-Permalloy and two mil Supermalloy. These tests were made by applying a 500 cycle voltage to the AC winding in series with a 1000 ohm resistor and a DC voltage to the control winding in series with a 350 ohm resistor. The oscilloscope was connected to show the drop across the 1000 ohm resistor and the DC voltage was adjusted to expend one microwatt of power in the control winding. The DC voltage was applied by closing a switch, and this triggered the single sweep trace of the oscilloscope to which the camera was attached. As the control field increased the impedance of the AC winding decreased, and the current in the 1000 ohm resistor increased to its steady state value. By counting the number of cycles occurring between the time of application of the control voltage and the attainment of the steady state value of AC, the response time was readily determined.

It was found that under the conditions described, the response time of the two mil Supermalloy inductor was eight milliseconds, and for the 4-79 Mo-Permalloy and the Deltamax it was 20 and 52 milliseconds, respectively. Reducing the value of either the 1000 ohm resistor or the 350 ohm resistor, increased the time.

In most applications it is expected that there will be a rather large value of resistance in series with the AC winding, and it is understood that the internal resistances of the pickups contemplated are usually a few hundred ohms. Therefore, it seems that it will be possible to secure suitable response times in practice.

L-C Oscillator Tests

When it was found that it would be impossible to design a controllable subminiature inductor having a Q of five or more, except in some isolated cases, it was considered desirable to find out if a Q of as much as five was actually required. Several attempts were made to construct an L-C oscillator using a low conductance vacuum tube and a pair of the specimen inductors that had been made. The circuit that provided the best operation is shown in Figure 97.

The Colpitts oscillator is ordinarily not difficult to adjust for good oscillation, but this one could not be made to oscillate until some bias was

applied to the control fields of the inductors. As will be seen by an examination of Figures 84 and 85, the application of bias increases the Q, and this is the reason that oscillation was secured with the application of some bias. However, it is also seen that the greatest inductance change for a given bias occurs for small values of bias, so it was found that after enough bias had been applied to secure oscillation, the addition of the amount of bias produced by one microwatt of power did not produce a large enough change of frequency.

It was also found impossible to secure oscillation at frequencies higher than about 2000 cycles.

The conclusion was drawn that the possibilities for the design of suitable subminiature DC controlled inductors for use in the tank circuits of L-C tuned oscillators were not good because of the difficulty involved in designing inductors having sufficiently high values of Q, while meeting the other requirements of the proposed application.

A New Oscillator

In considering the matter of designing inductors having suitably high values of Q, the idea was conceived that it might be possible to make use of the fact that all of the inductors we had constructed had high values of effective resistance. Consequently, the oscillator of Figure 98 was built and tested. It is described in more detail in Appendix B.

An improved modification of this oscillator is shown in Figure 99. It will be noted that this is an R-C oscillator in which the capacitance is fixed, and the resistance is variable. The controlled subminiature inductor is used as a DC controlled resistance, use being made of the high effective resistance of an inductor having a low value of Q.

This circuit has several advantages, the first and most important one being that its use makes possible the frequency modulation of a carrier with one microwatt of control power. The realization of this possibility was one of the principal objectives of this investigation. A second advantage is that a single inductor is used in the oscillator, and it does not need to have matched windings, and since there is only one core involved, there is no need for matched cores. A third advantage is that several different materials can probably be used since the Q values of inductors used in this manner are not critical, although the thin gage Supermalloy seems to provide the best results when all factors are considered.

It will be emphasized at this point that the conception of this oscillator did not occur until rather late in the investigation, and for this reason only a limited number of tests were made to determine its possibilities. It seems desirable, in view of the importance of this development, that a comprehensive investigation of this oscillator should be started as soon as possible. This investigation should include a study of the frequency ranges over which satisfactory operation can be secured, a comparison of thin gage Supermalloy, 4-79 Mo-Permalloy and Deltamax for core materials for the inductors used in this

circuit; a study of the response times that can be secured; and an investigation of reproducibility as affected by residual magnetism and external fields. It is expected that such an oscillator would be constructed using transistors, in order to reduce size and weight, and, perhaps, to make possible the use of hermetically sealed, vibration-proof units and small batteries.

Inductor Design for the New Oscillator

The development of the new oscillator previously described made clear the fact that suitable inductors could be designed to operate with a microwatt of control power. The two mil Supermalloy cores had been selected as the ones having the best possibilities when it was believed that Q values of five or more would be required. When this requirement was found to be nonexistent, it was decided that, although the Supermalloy would probably be the best, some of the other materials, such as 4-79 Mo-Permalloy and Deltamax, might also be satisfactory.

Since it was believed that Supermalloy would be the best, it seemed that a complete set of data on this particular material should be secured, and a core of 0.002" thick tape wound Supermalloy in the #5340 size was used to secure the data shown in Figures 86 to 95, inclusive.

A detailed procedure for using these data to design inductors that will be satisfactory for operation in the R-C oscillator described in Appendix B was also developed and is described in Appendix C.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A study of the data secured during this investigation resulted in the following conclusions concerning the use and design of variable subminiature inductors (for telemetering systems) to be operated in the frequency range from 500 cycles to one megacycle, and to be controlled by not more than one microwatt of DC control power:

1. Such inductors are practical for use in amplitude modulated systems, but the impedances of these inductors include large components of effective resistance. The Q values, consequently, are low. However, both the inductance and the effective resistance of the inductor decreases as the DC control field increases so the net result is suitable for an amplitude modulated system.

2. The low Q values that must be tolerated in the design of these subminiature inductors make them generally unsuitable for use in L-C tuned circuits such as in the tank circuits of L-C tuned oscillators.

3. The use of a new type of oscillator, in which the effective resistance of the subminiature inductor is controlled to cause oscillator frequency variation, makes a frequency modulation system practical with the use of inductors having low values of Q. Such an oscillator was constructed and tested.

4. Subminiature variable inductors of the type described will normally be operated at relatively low peak AC inductions to avoid large harmonics in the exciting current, to reduce the core losses in the inductors and to secure the most control with the small amounts of DC control power available.

5. The oscillators described are practical for operation at frequencies at least as high as from 50 to 100 kilocycles. It is not known at this time what the upper frequency limits of these oscillators may be.

6. The most suitable core construction is the tape wound toroidal core. This type of core involves the minimum air gap, and is the most practical kind for the use of the high permeability, high quality magnetic materials. The use of ferrites and powdered core materials does not permit the attainment of the required amount of inductance or impedance control with the available DC control power. Materials thicker than 0.003" will, in general, be unsuitable for use with these inductors. Tapes thinner than 0.001" are somewhat difficult to secure, and are relatively expensive at the present time. Cores made of punched laminations are unsuitable for this application. The same is true for "cut", or "C", cores.

7. The most suitable size of core for this application is known as the #5340 size, which is a designation by the Arnold Engineering Company of Marengo, Illinois. This core has the following dimensions: I. D. 0.50", O. D. 0.75" and H 0.125". In order to protect the high quality cores from mechanical strain,

they are enclosed in standard Nylon containers having the following dimensions: I. D. 0.440", O. D. 0.810" and H 0.195". The major portion of the cost of one of these small cores is labor cost, so the cost is not affected greatly by the material used in the core. This is particularly true of the thinnest gages.

8. The maximum amount of control magnetizing force that can be secured with one microwatt of DC control power expended in a practical winding on a suitable sized core of suitable construction, is approximately 0.05 ampere turns per centimeter of core length.

9. The most suitable materials for use in the tape wound cores are the thin gages of Supermalloy, 4-79 Mo-Permalloy and Deltamax, in the order listed. The first two are considerably better than the last one, for this particular application.

10. The Supermalloy material is the best from the standpoint of the amount of control secured with a given amount of bias field. Since it is necessary to use resistances in the external circuits to secure adequate time response, it is desirable that the inductor alone should provide as much change of impedance for a given amount of control power as possible, in order to permit the use of external resistors without reducing the amount of control secured below adequate levels.

11. Transverse bias fields are not useful for control purposes. If they are uniform, and truly transverse, they have negligible effects on the incremental permeabilities and losses of the cores. Fields encountered in practice would be neither uniform nor truly transverse, so there would usually be a component that would alter the effect of the control field. The earth's field is not strong enough to effect the cores described, but they should be shielded from stronger fields.

12. Uncontrolled residual magnetism in the cores will cause variations in the response to a given amount of control. The magnetizing forces produced by the normal operating currents in the windings will not cause difficulties due to residual fields, but the cores should be demagnetized immediately before calibration and shielded from external fields, in order to avoid such difficulties.

13. Electrical, or magnetic noise, is not a problem at the power and voltage levels involved.

14. The maximum rate of change of inductance and effective resistance for a specified change of control field occurs in the region increasing from zero DC bias. For this reason, it is not probable that external bias sources, such as permanent magnets, will be useful in most cases.

15. Values of effective resistance and inductance normally required will be attainable at the required operating voltage levels. The data included on 0.002" Supermalloy will be adequate for use in designing inductors for amplitude modulation systems, and for use in oscillators similar to the one described in Appendix B.

The following recommendation are presented:

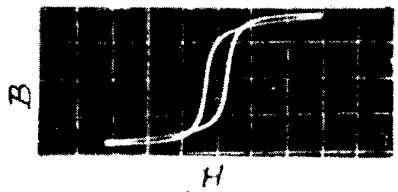
1. A project should be initiated for the study of the oscillator developed during the progress of this investigation. This study should include tests to determine particularly the frequency limitations of this oscillator as well as other operating characteristics.

2. In order to measure time response, tests of this oscillator in operation with a typical pickup device should also be made.

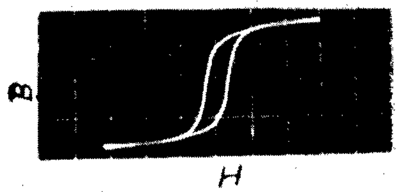
3. The characteristics necessary in variable subminiature inductors to be used as controlled resistors in such an oscillator should be determined so they can be readily designed from the magnetic data available.

4. The use of transistors in the proposed oscillator should be investigated with the objectives of attaining small size, hermetically sealed, vibration-proof assemblies.

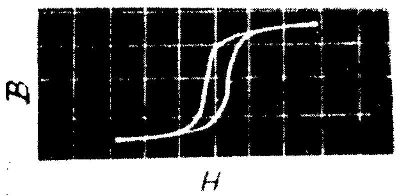
DYNAMIC HYSTERESIS LOOPS
OF
CERAMAG 5N FERRITE
AT
VARIOUS FREQUENCIES
D. C. BIAS – 0



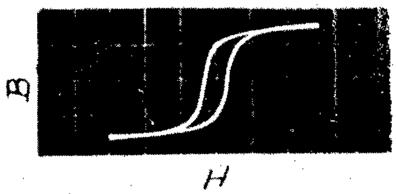
50 KILOCYCLES
FIG. 1



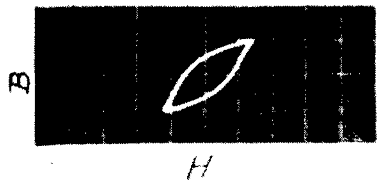
75 KILOCYCLES
FIG. 2



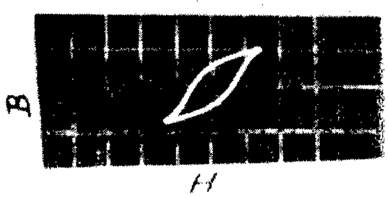
100 KILOCYCLES
FIG. 3



120 KILOCYCLES
FIG. 4

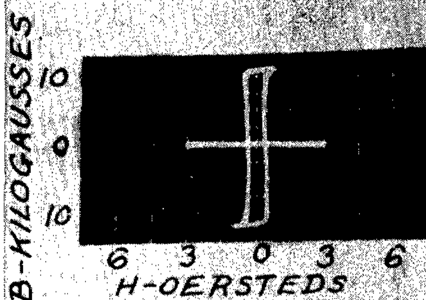


10 KILOCYCLES
FIG. 5

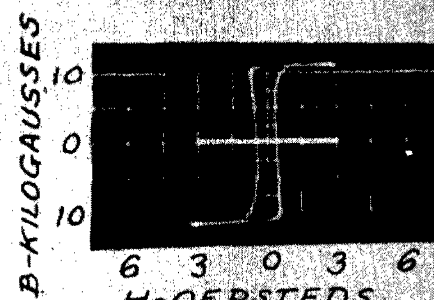


100 KILOCYCLES
FIG. 6

DYNAMIC HYSTERESIS LOOPS
OF
VARIOUS CORE MATERIALS
AT
10 KILOCYCLES
D.C. BIAS-0

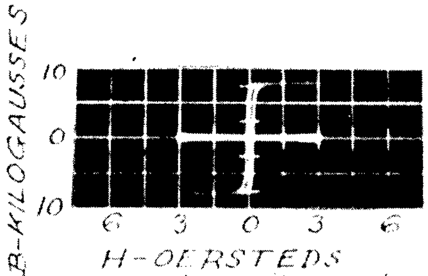


0.001" MONIMAX
FIG. 7

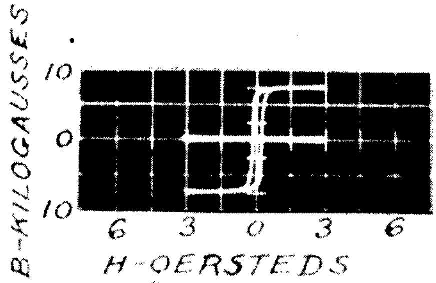


0.001" MONIMAX
FIG. 8

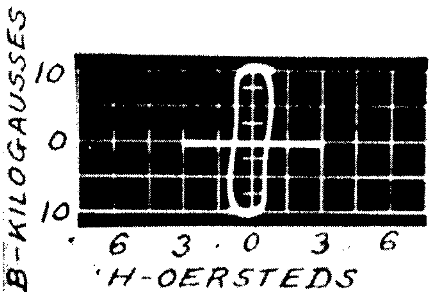
DYNAMIC HYSTERESIS LOOPS
OF
VARIOUS CORE MATERIALS
AT
10 - KILOCYCLES
D. C. BIAS - 0



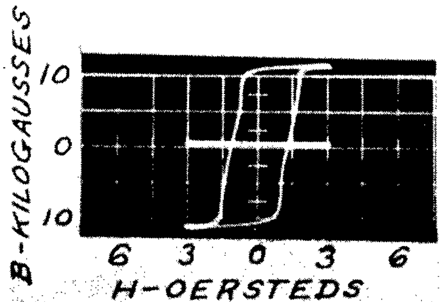
0.001" SUPERMALLOY
FIG. 11



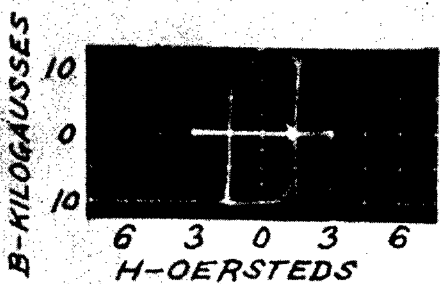
0.001" 4-79 Mo PERMALLOY
FIG. 12



0.003" MONIMAX
FIG. 13

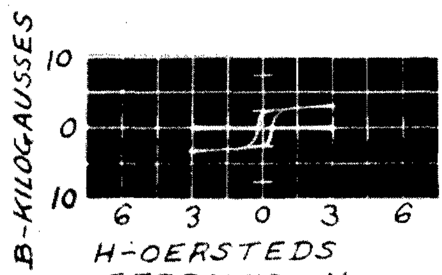


0.003" MONIMAX
FIG. 14

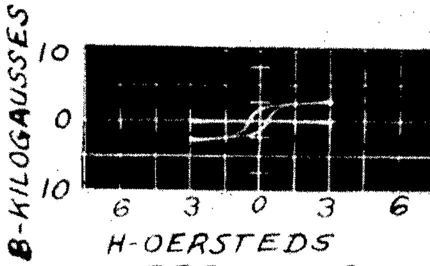


0.002" SX-10
FIG. 15

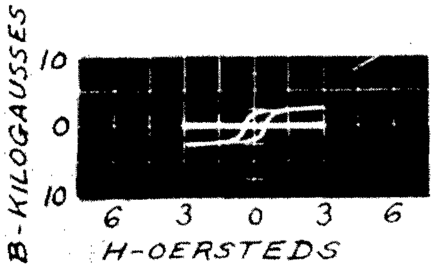
DYNAMIC HYSTERESIS LOOPS
OF
VARIOUS CORE MATERIALS
AT
10 KILOCYCLES
D. C. BIAS — O



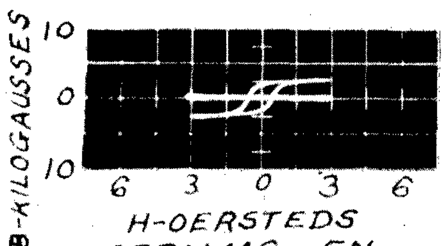
FERRAMIC H
FIG. 16



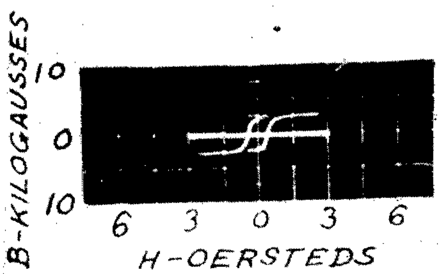
FERRAMIC G
FIG. 17



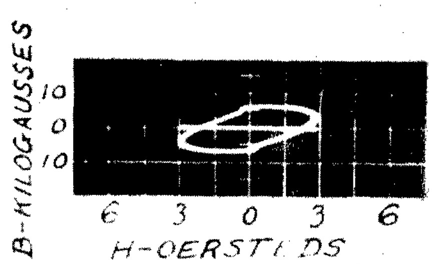
CERAMAG 7
FIG. 18



CERAMAG 5N
FIG. 19

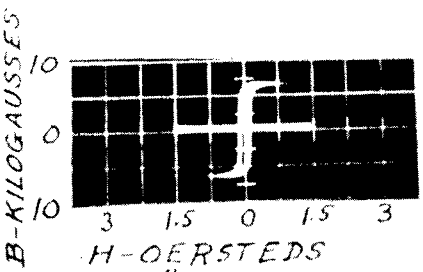


CERAMAG 8
FIG. 20

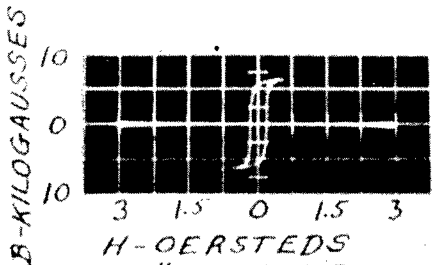


0.006" HYMU 80
FIG. 21

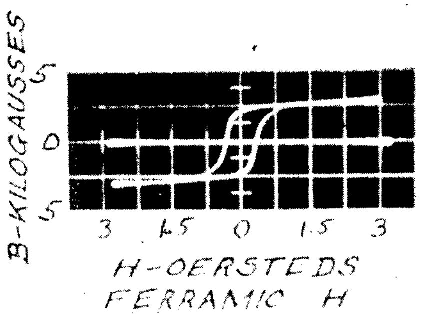
DYNAMIC HYSTERESIS LOOPS
FOR
COMPARISON OF SIMILAR MATERIALS
AT
10 KILOCYCLES



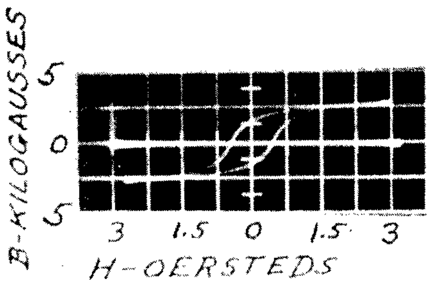
0.001" SUPERMALLOY
FIG. 22



0.001" 4-79 MoPERMALLOY
FIG. 23

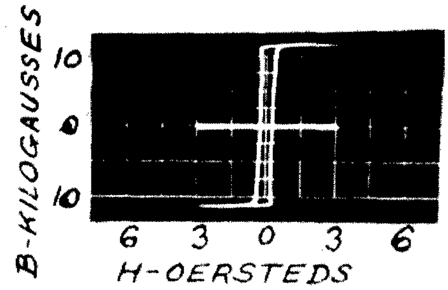


FERRAMIC H
FIG. 24

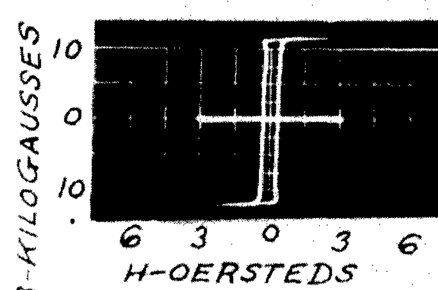


FERRAMIC G
FIG. 25

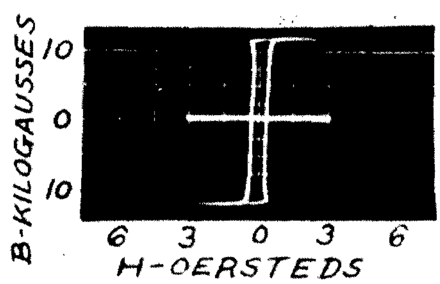
DYNAMIC HYSTERESIS LOOPS
OF
VARIOUS CORE MATERIALS
AT
500 CYCLES
D. C. BIAS—O



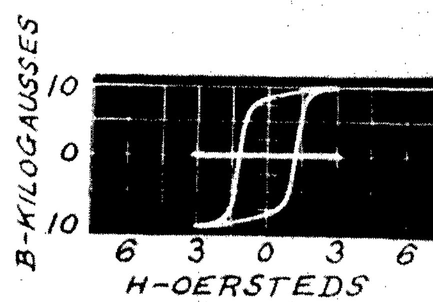
0.001" MONIMAX
FIG. 26



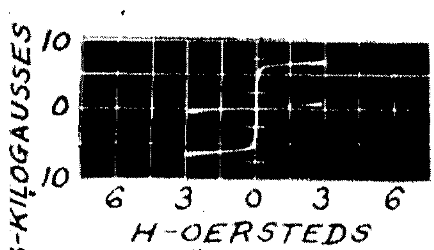
0.002" MONIMAX
FIG. 27



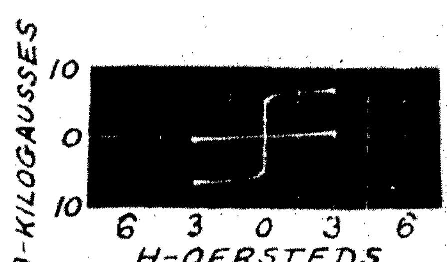
0.003" MONIMAX
FIG. 28



0.010" MONIMAX
FIG. 29

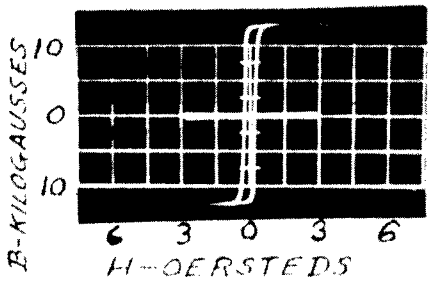


0.001" SUPERMALLOY
FIG. 30

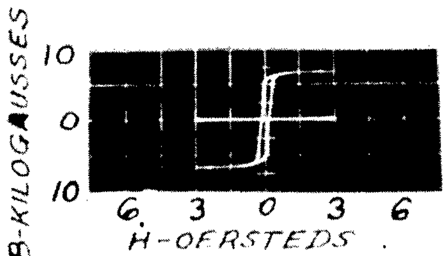


0.001" 4-79 MoPERMALLOY
FIG. 31

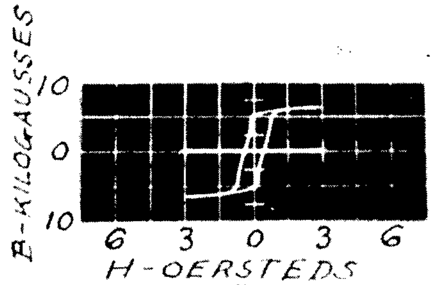
DYNAMIC HYSTERESIS LOOPS
OF
VARIOUS CORE MATERIALS
AT
500 CYCLES
D. C. BIAS -- 0



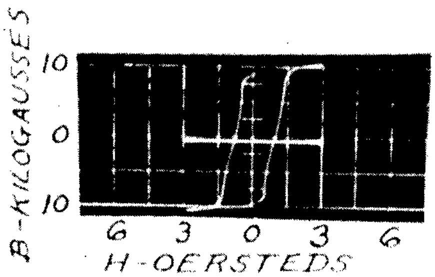
0.001" DELTAMAX
FIG. 32



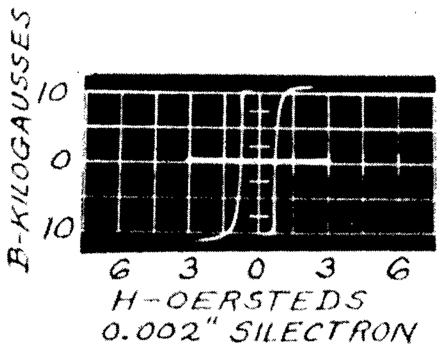
0.006" HyMu 80
FIG. 33



0.010" MuMetal
FIG. 34

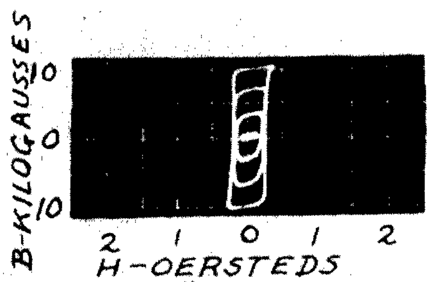


0.010" 47-50
FIG. 35

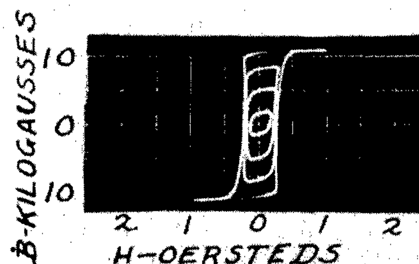


0.002" SILECTRON
FIG. 36

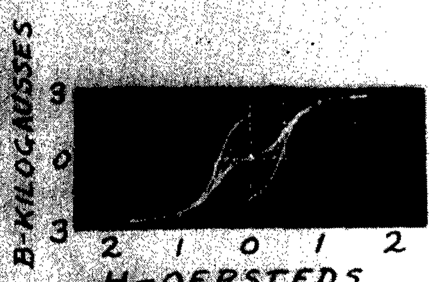
DYNAMIC HYSTERESIS LOOPS
FOR THE
DERIVATION OF A. C. MAGNETIZATION CURVES
AT
VARIOUS FREQUENCIES



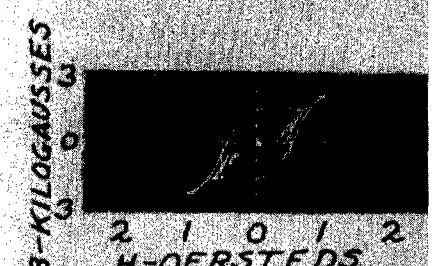
0.001" DELTAMAX
500 C. P. S.
FIG. 37



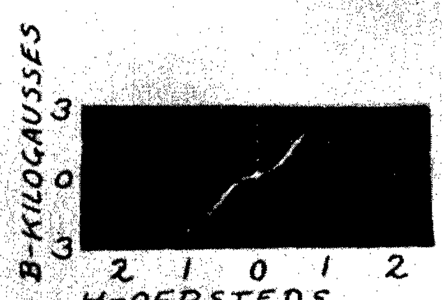
0.001" DELTAMAX
500 C. P. S.
FIG. 38



CERAMAG 5N
10 KILOCYCLES
FIG. 39



CERAMAG 5N
100 KILOCYCLES
FIG. 40



CERAMAG 5N
10 KILOCYCLES
FIG. 41

DYNAMIC HYSTERESIS LOOPS
FOR
DETERMINATION OF A. C. MAGNETIZATION CURVE
OF
0.002" SUPERMALLOY
AT 500 CYCLES

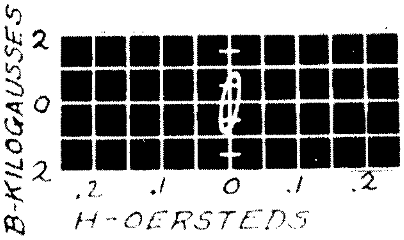


FIG. 42

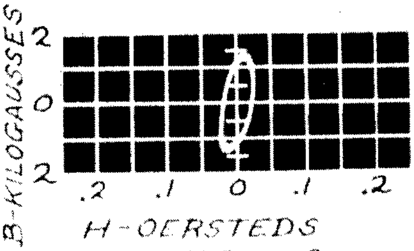


FIG. 43

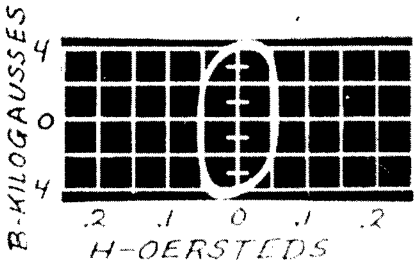


FIG. 44

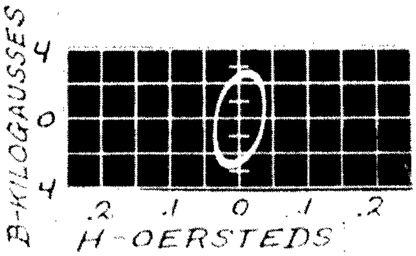


FIG. 45

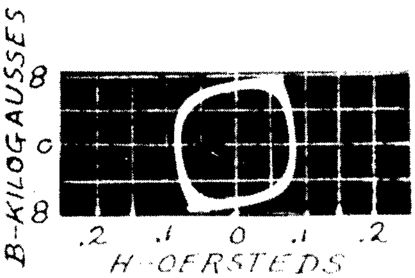


FIG. 46

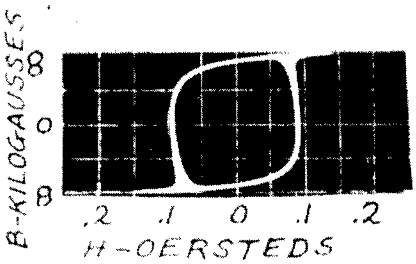


FIG. 47

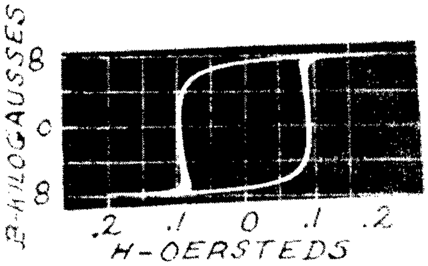


FIG. 48

DYNAMIC HYSTERESIS LOOPS
FOR
DETERMINATION OF A.C. MAGNETIZATION CURVE
OF
0.001" 4-79 Mo PERMALLOY
AT 500 CYCLES

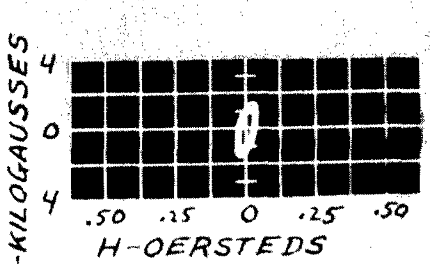


FIG. 49

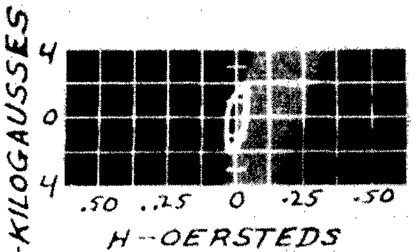


FIG. 50

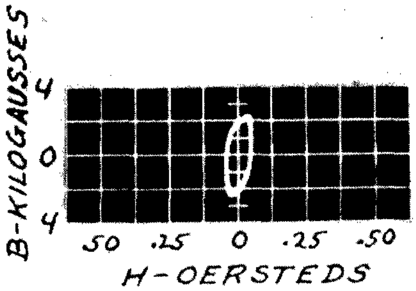


FIG. 51

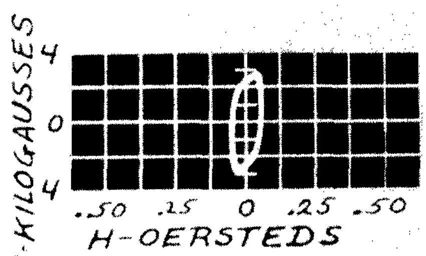


FIG. 52

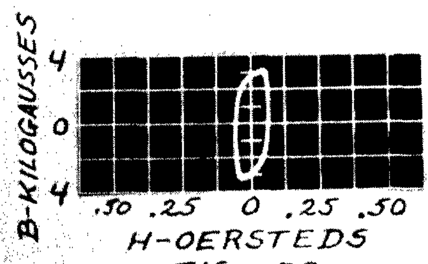


FIG. 53

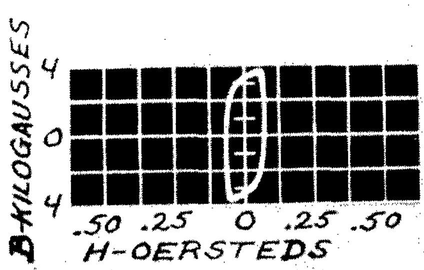


FIG. 54

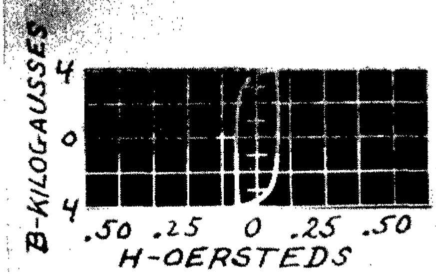


FIG. 55

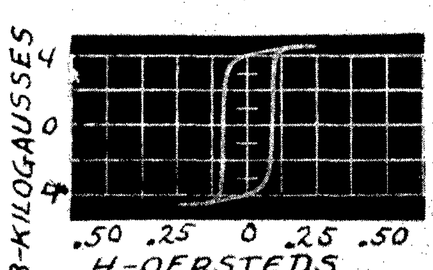


FIG. 56

DYNAMIC HYSTERESIS LOOPS
FOR
DETERMINATION OF A. C. MAGNETIZATION CURVE
OF
0.002" 47-50 MATERIAL
AT 500 CYCLES

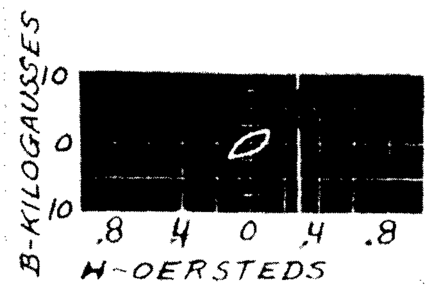


FIG. 57

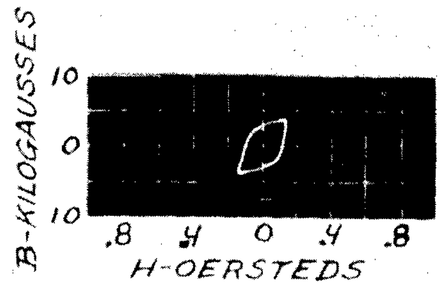


FIG. 58

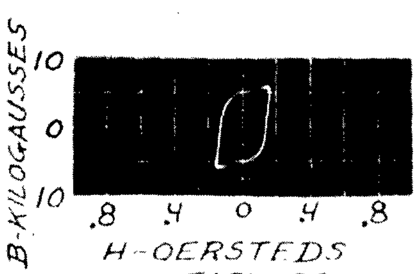


FIG. 59

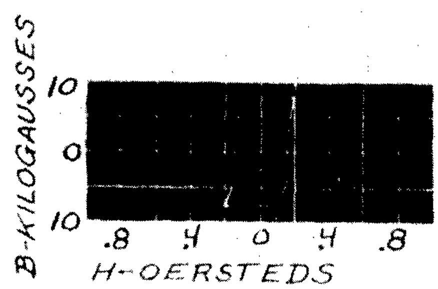


FIG. 60

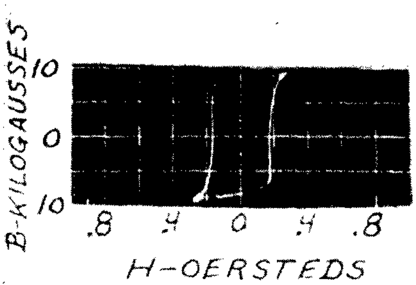


FIG. 61

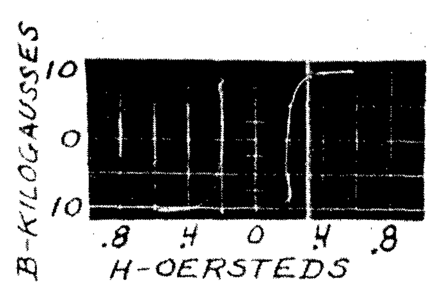
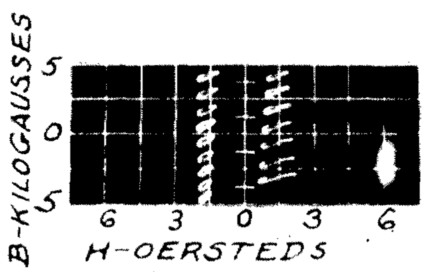
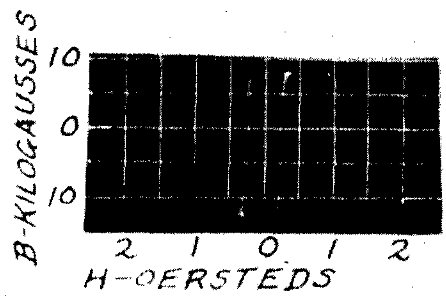


FIG. 62

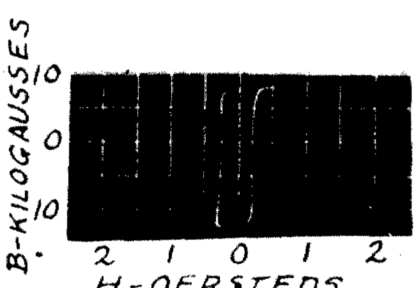
DYNAMIC HYSTERESIS LOOPS
FOR THE
DETERMINATION OF THE EFFECTS
OF
D. C. BIAS FIELDS ON A. C. PERMEABILITY
OF
0.001" DELTAMAX CORE MATERIAL
AT 500 CYCLES PER SECOND



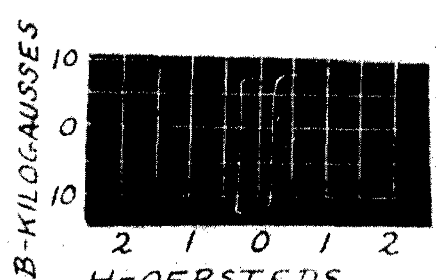
D. C. BIAS - 0 TO 0.37 $\frac{AT}{CM}$
FIG. 63



D. C BIAS — 0
FIG 64

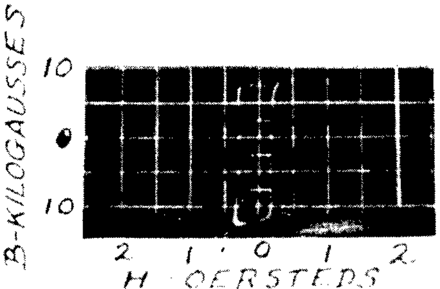


D. C BIAS - 0.01 $\frac{AT}{CM}$
FIG. 65

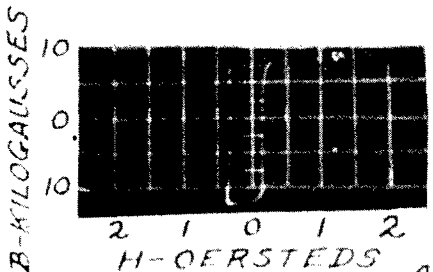


D. C. BIAS - 0.02 $\frac{AT}{CM}$
FIG. 66

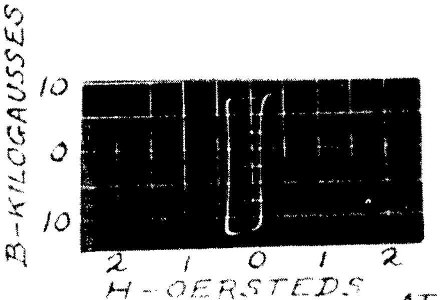
DYNAMIC HYSTERESIS LOOPS
FOR THE
DETERMINATION OF THE EFFECTS
OF
D. C. BIAS FIELDS ON A C. PERMEABILITY
OF
0.001" DELTAMAX CORE MATERIAL
AT 500 CYCLES PER SECOND



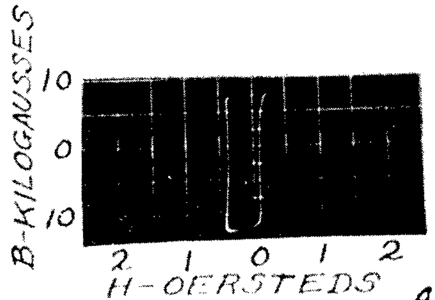
D. C. BIAS – 0.04 $\frac{AT}{cm.}$
FIG. 67



D. C. BIAS – 0.06 $\frac{AT}{cm.}$
FIG. 68

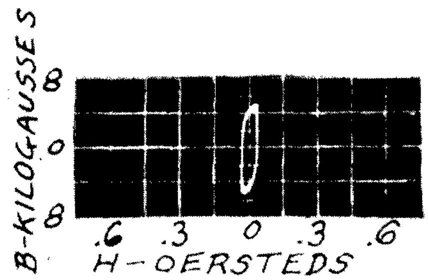


D. C. BIAS – 0.08 $\frac{AT}{CM}$
FIG. 69

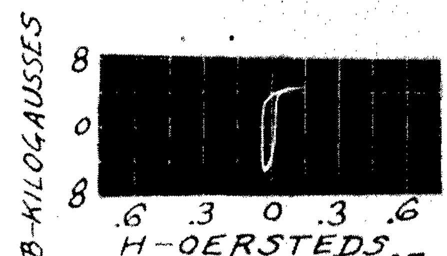


D. C. BIAS – 0.10 $\frac{AT}{CM.}$
FIG. 70

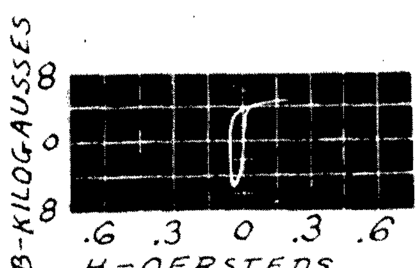
DYNAMIC HYSTERESIS LOOPS
FOR THE
DETERMINATION OF EFFECTS
OF
D. C. BIAS FIELDS ON A. C. PERMEABILITY
OF
0.002" SUPERMALLOY CORE MATERIAL
AT
500 CYCLES PER SECOND



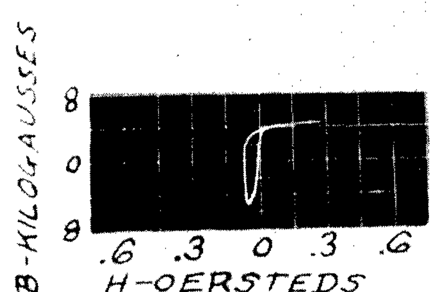
D.C. BIAS — 0
FIG. 71



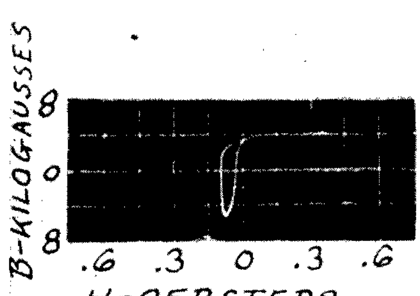
D. C. BIAS — 0.01 $\frac{AT}{CM.}$
FIG. 72



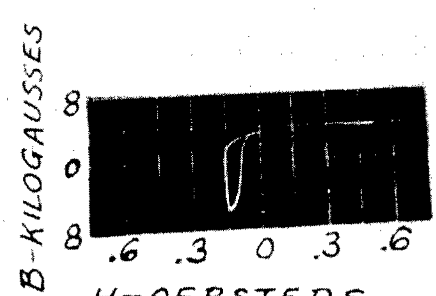
D. C. BIAS — 0.02 $\frac{AT}{CM.}$
FIG. 73



D. C. BIAS — 0.03 $\frac{AT}{CM}$
FIG. 74



D. C. BIAS — 0.05 $\frac{AT}{CM}$
FIG. 75



D. C. BIAS — 0.10 $\frac{AT}{CM}$
FIG. 76

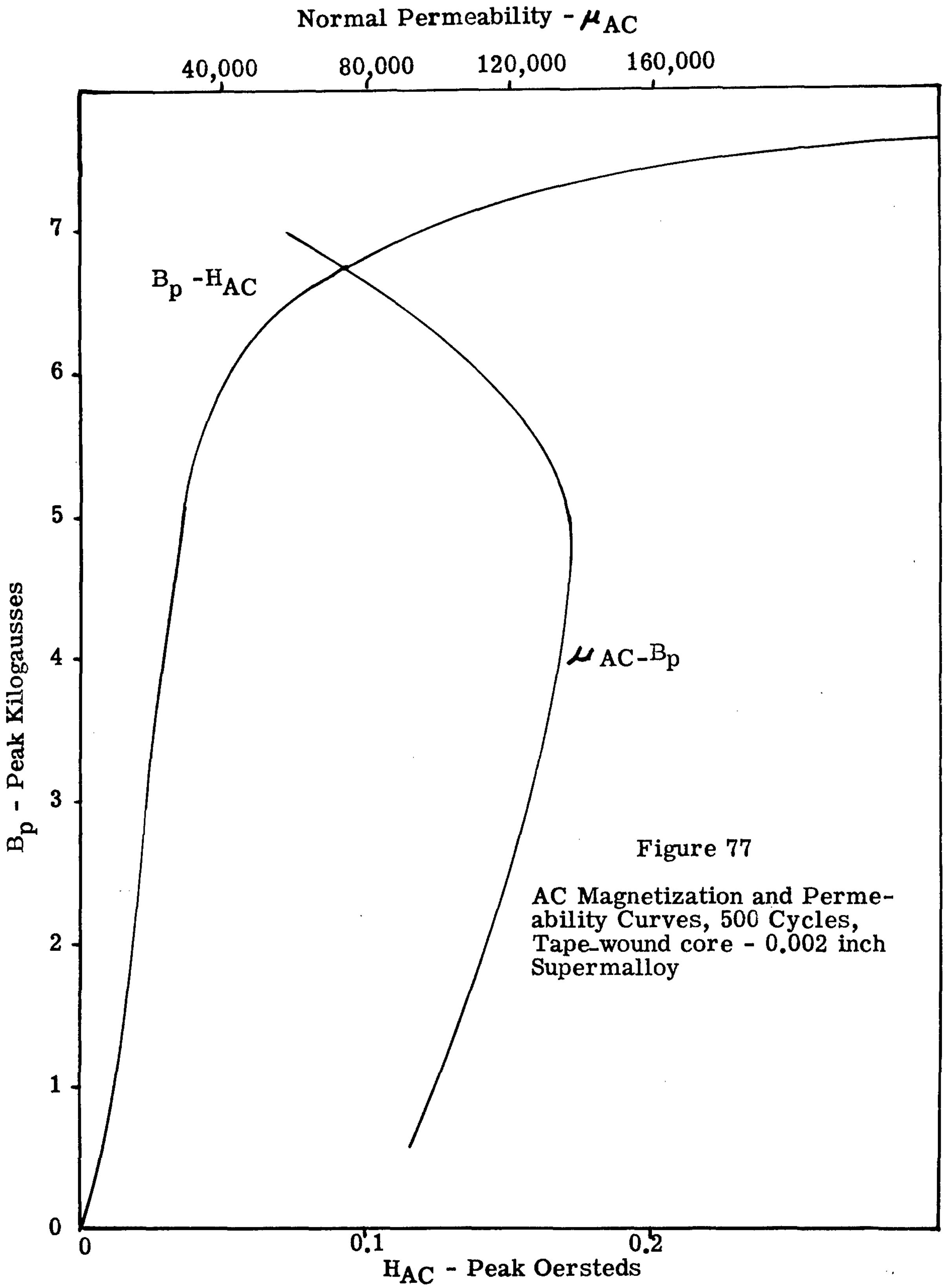


Figure 77

AC Magnetization and Permeability Curves, 500 Cycles, Tape-wound core - 0.002 inch Supermalloy

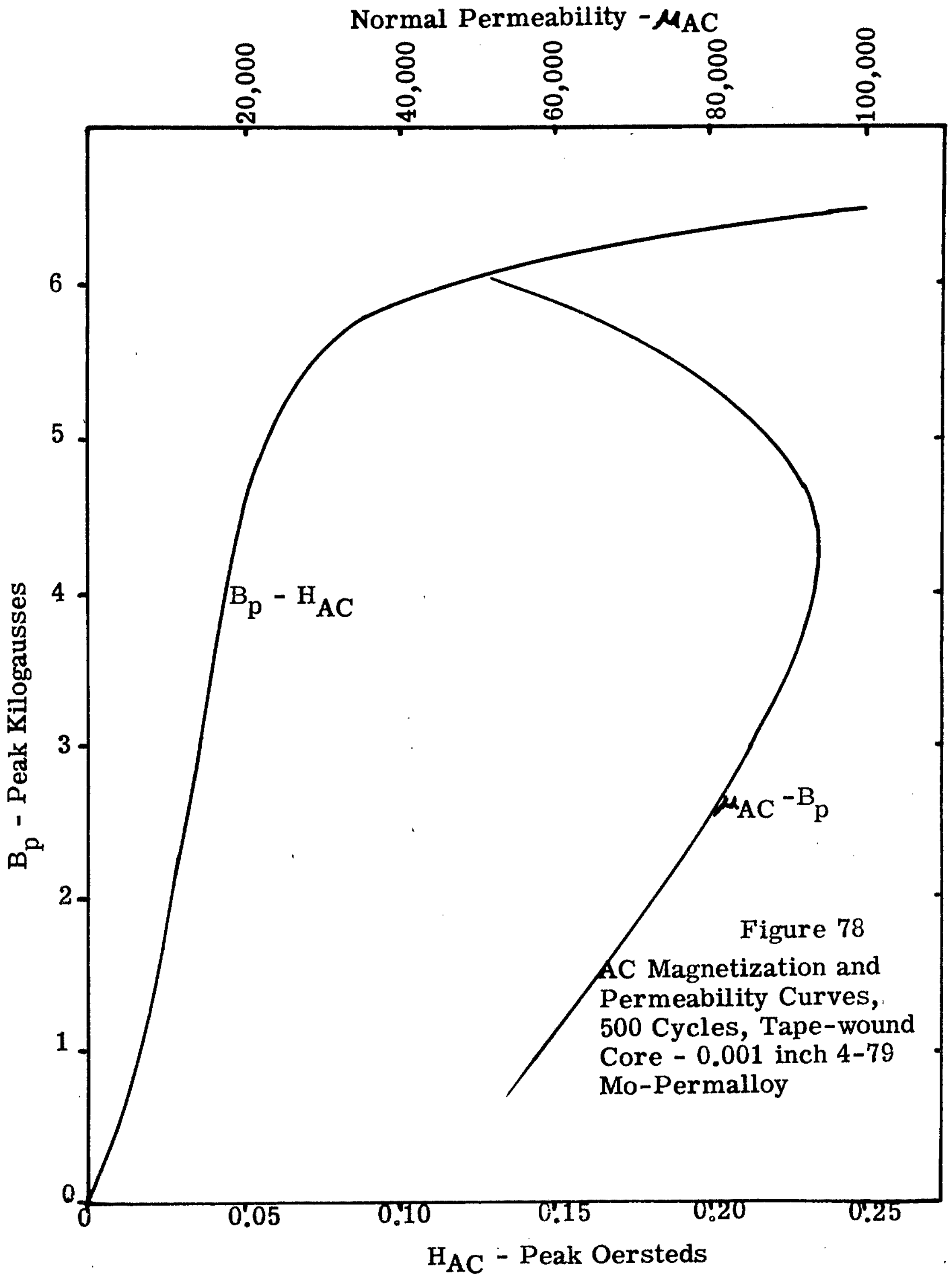


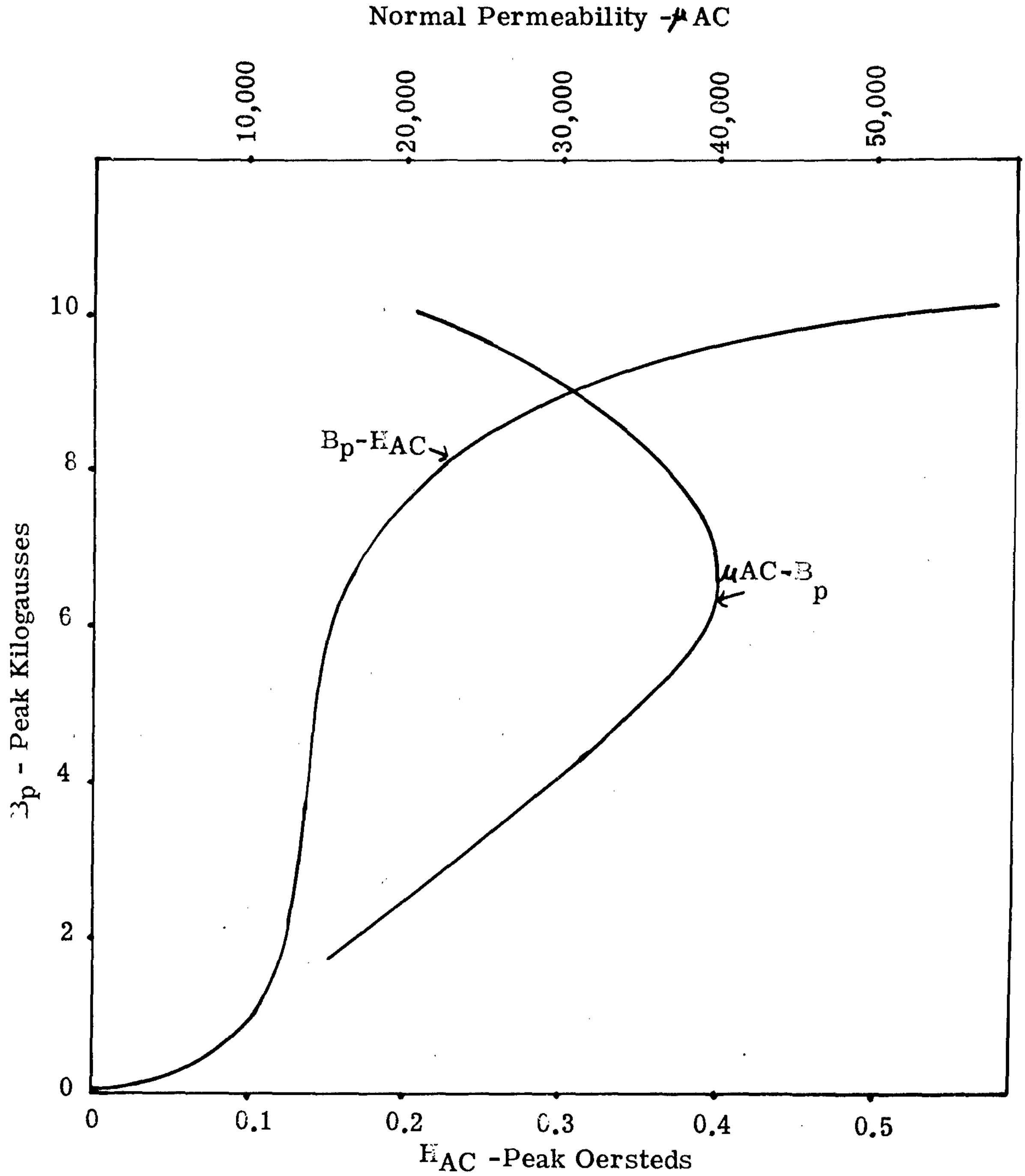
Figure 78
AC Magnetization and Permeability Curves, 500 Cycles, Tape-wound Core - 0.001 inch 4-79 Mo-Permalloy

Figure 79

AC Magnetization and Permeability Curves

500 Cycles, Tape-wound core - 0.002 inch

47-50 Alloy



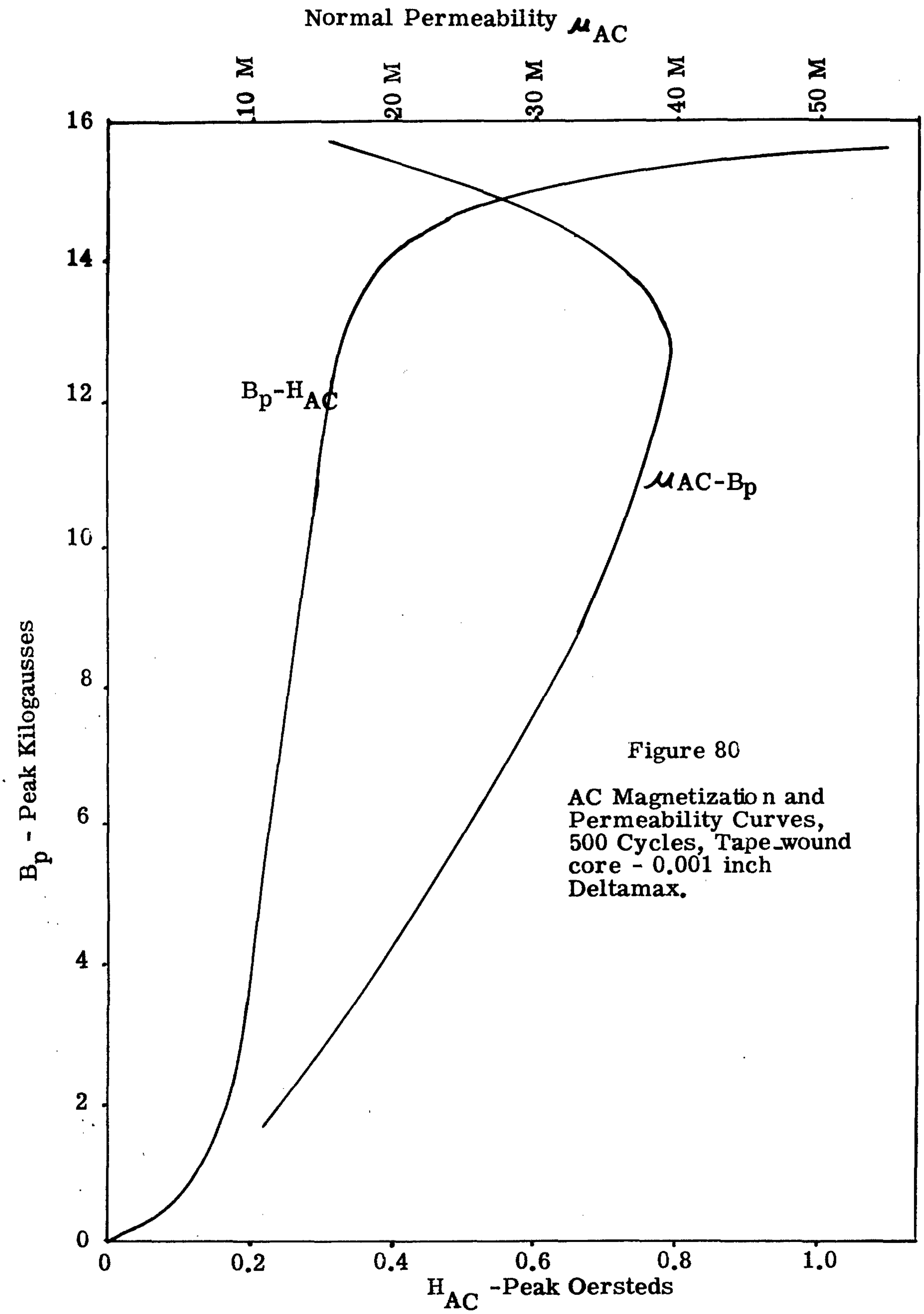


Figure 80

AC Magnetization and Permeability Curves, 500 Cycles, Tape-wound core - 0.001 inch Deltamax.

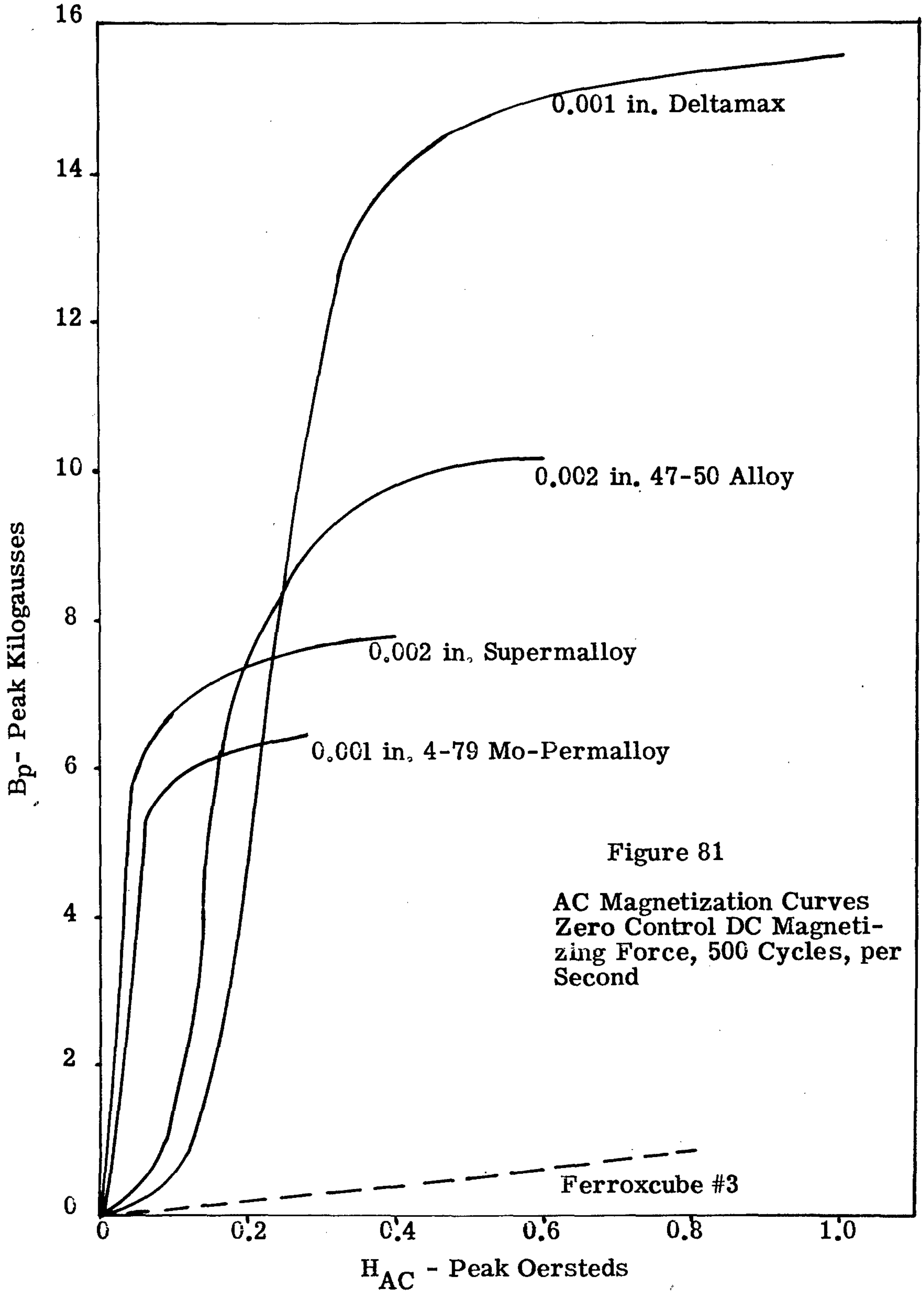


Figure 81

AC Magnetization Curves Zero Control DC Magnetizing Force, 500 Cycles, per Second

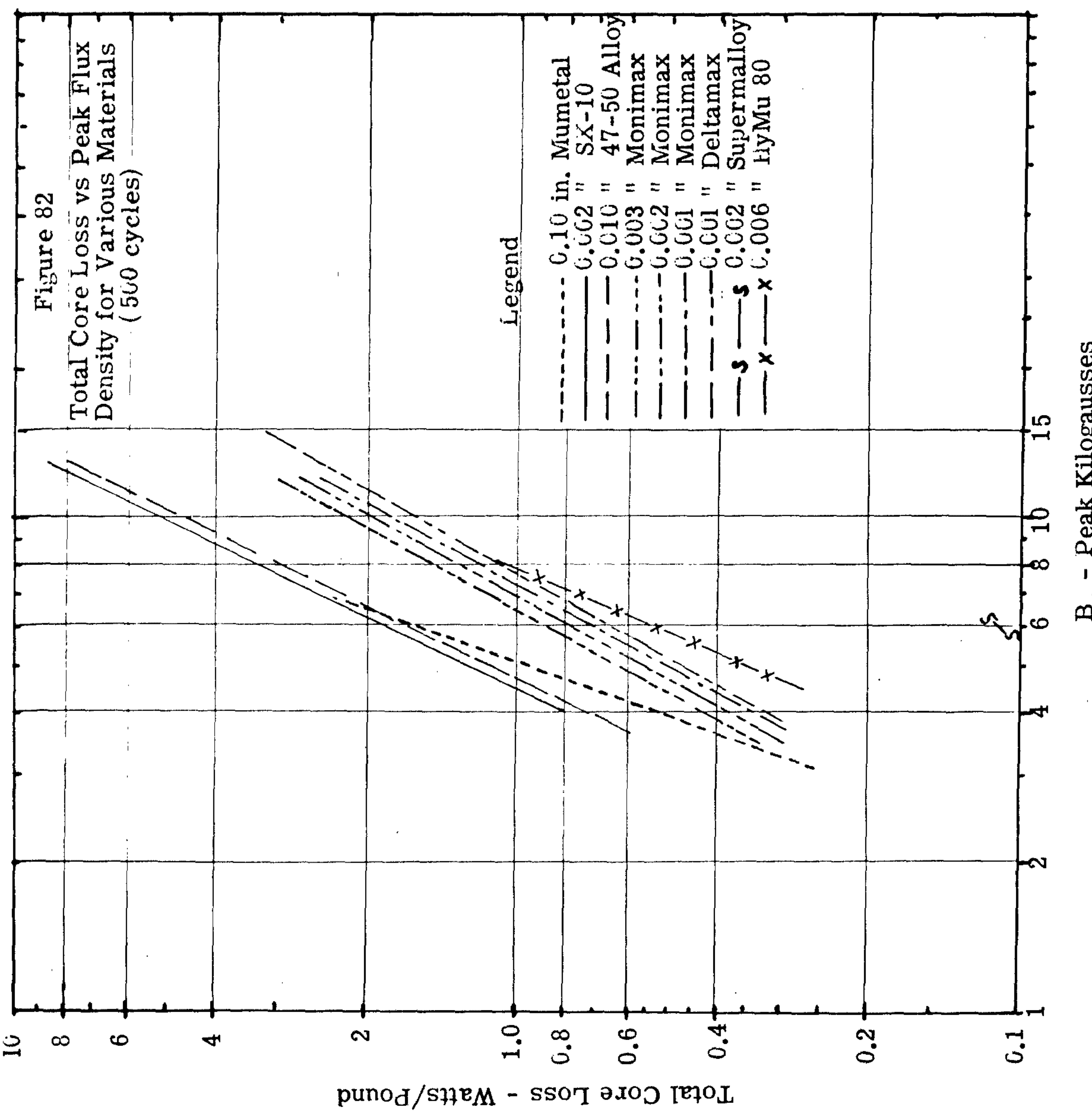


Figure 82
Total Core Loss vs Peak Flux Density for Various Materials
(500 cycles)

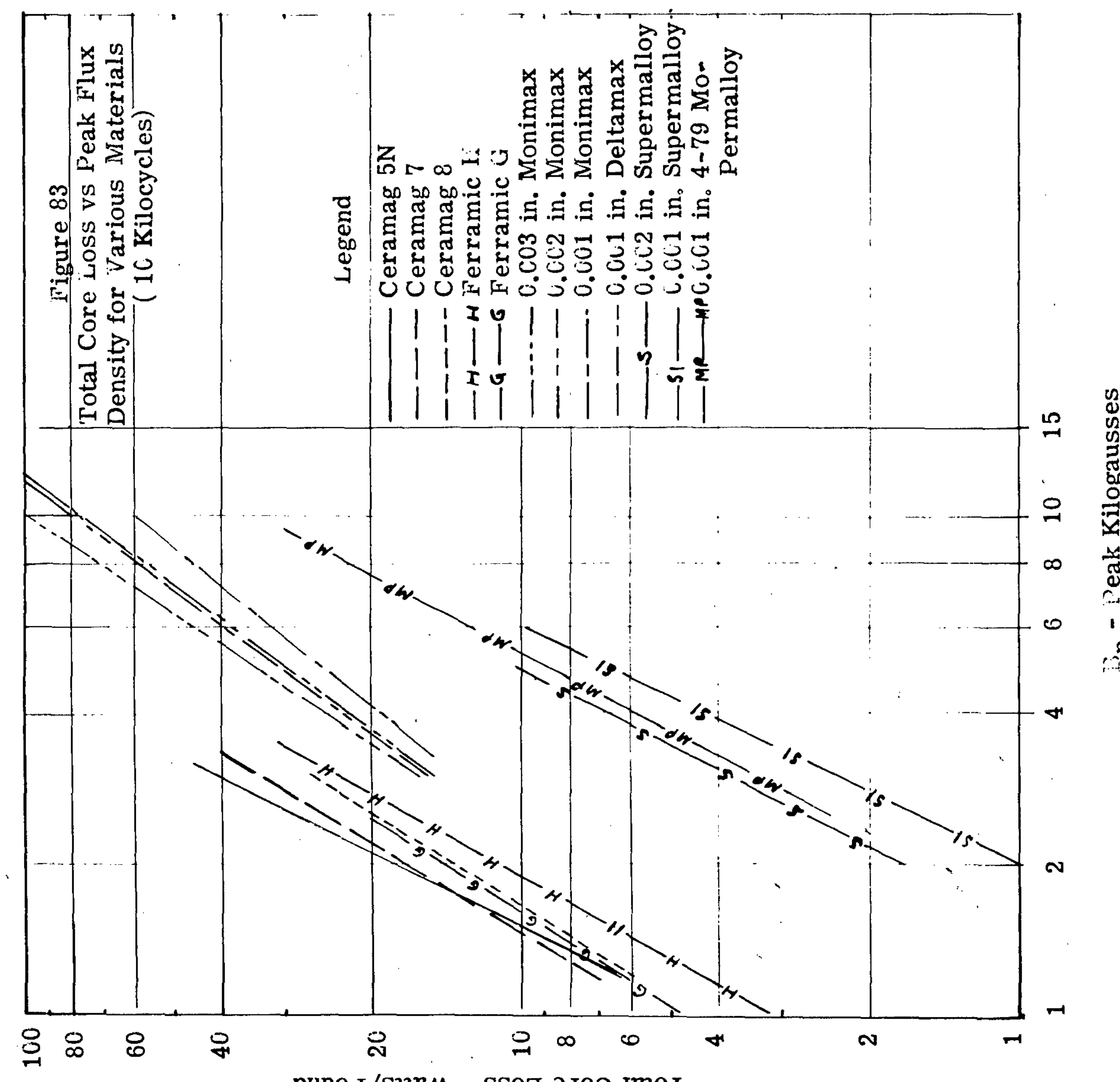


Figure 83
Total Core Loss vs Peak Flux Density for Various Materials
(10 Kilocycles)

Figure 84

Impedance Characteristics vs DC Control Field
Material: 0.002 in. Supermalloy, magnetizing turns; 500
Frequency: 500 Cycles, flux density 500 gausses.

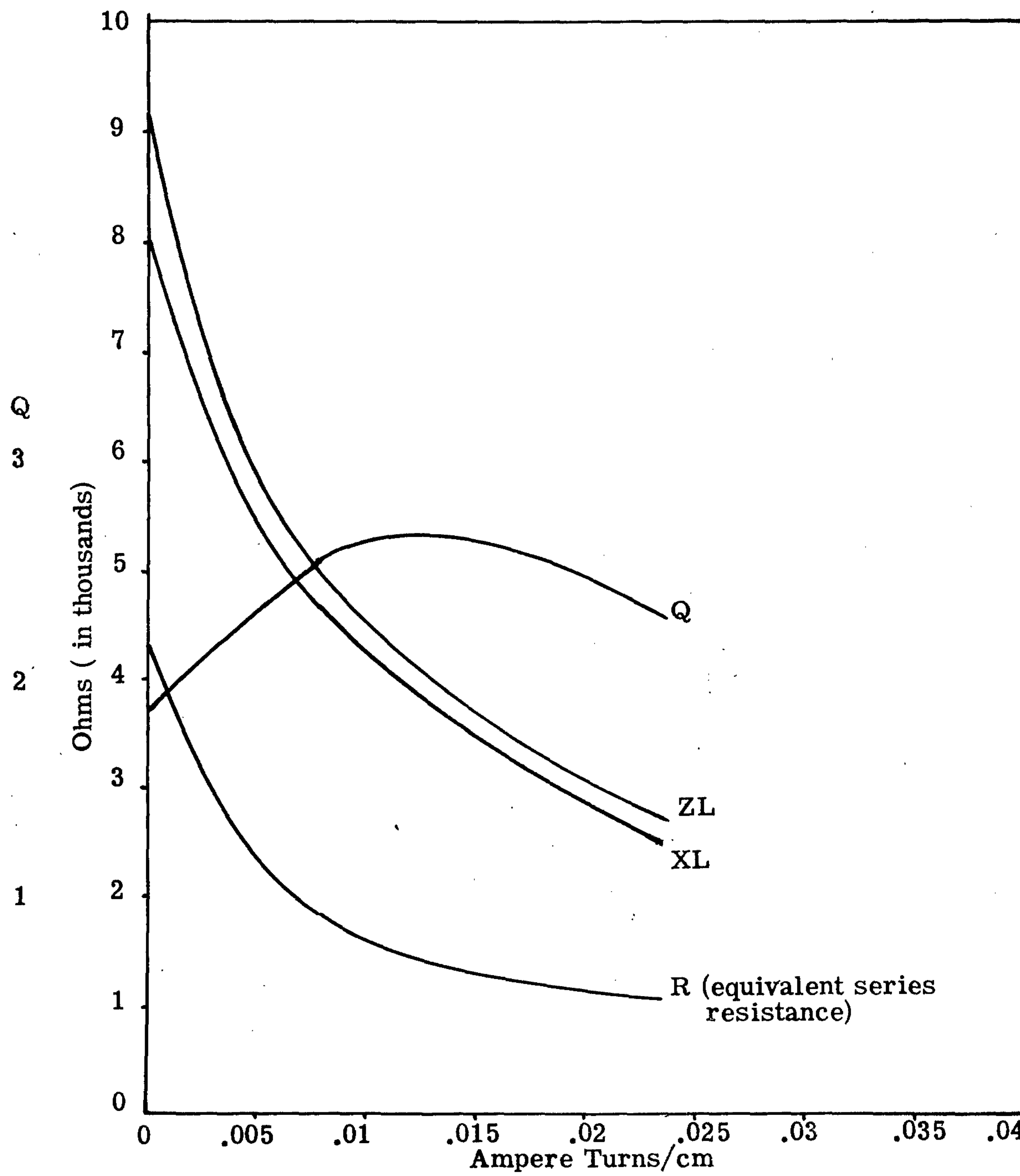


Figure 85

Impedance Characteristics vs DC Control Field
Material: 0.002 in. Supermalloy, magnetizing turns: 500
Frequency: 500 Cycles, flux density 1100 gausses

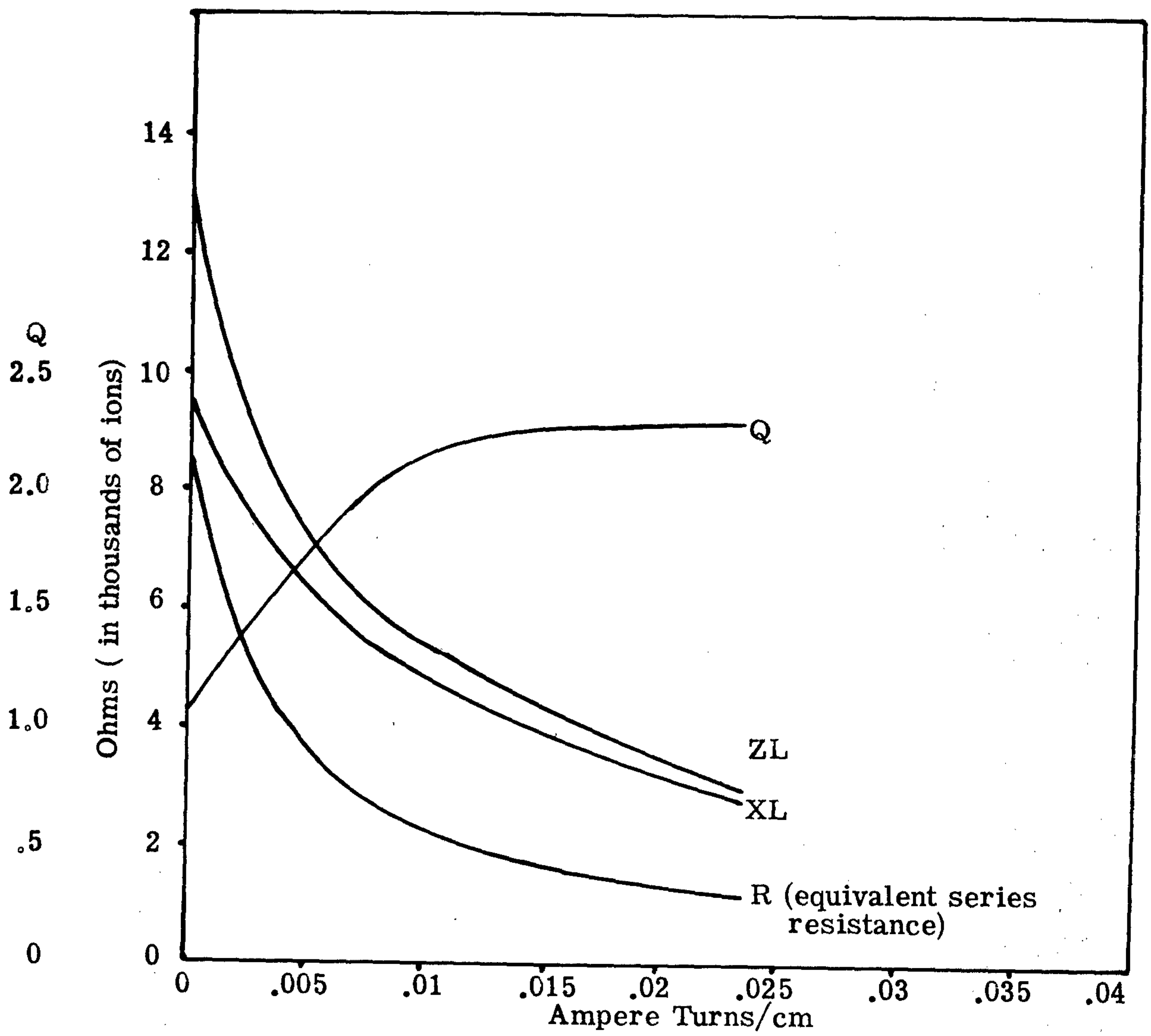
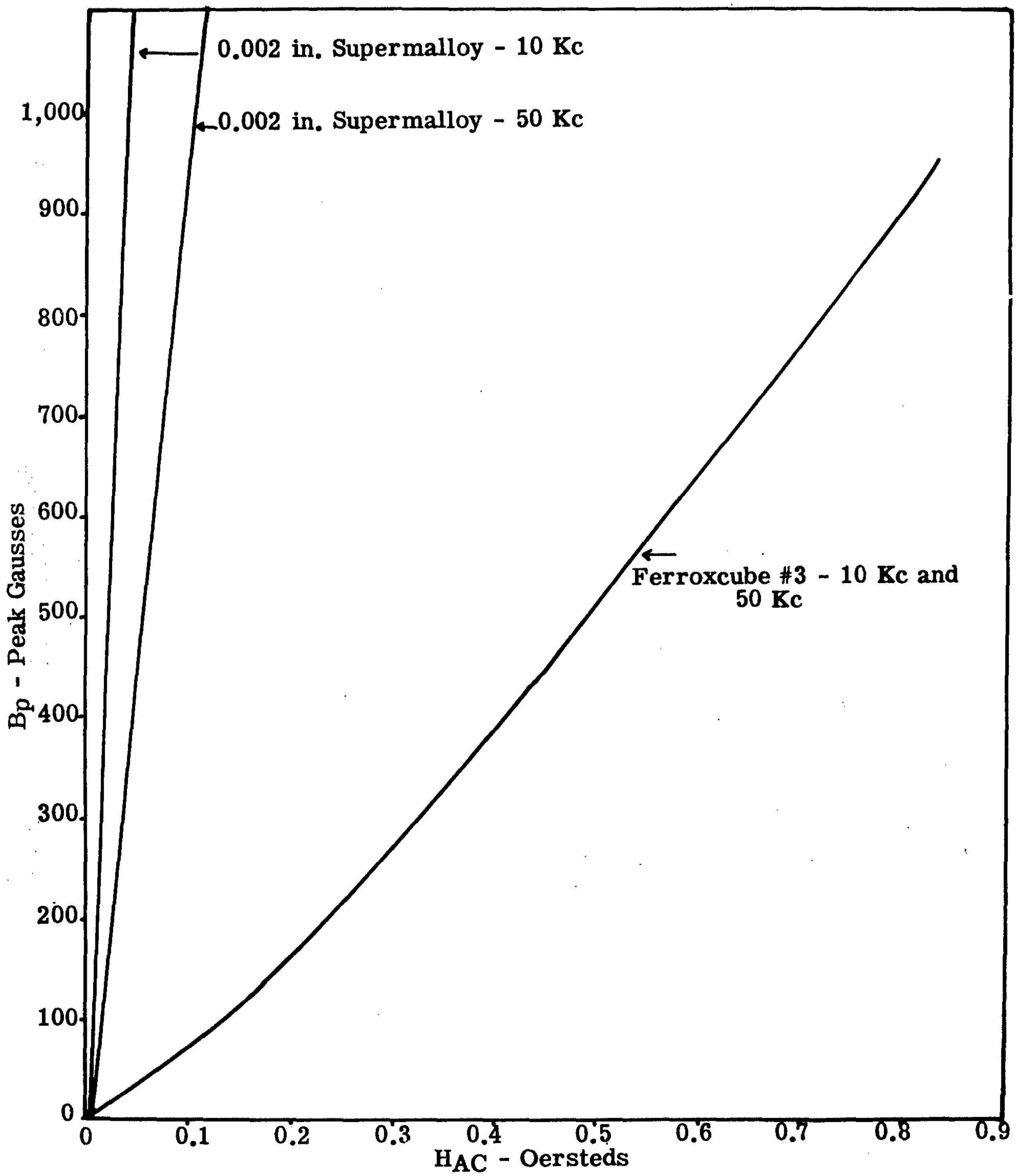


Figure 86

Low Density, AC Magnetizing Curves
for Comparison, 10 and 50 Kilocycles
Size # 5340 Tape wound core - 0.002 in.
Supermalloy and Ferrocube #3 Ferrite Core



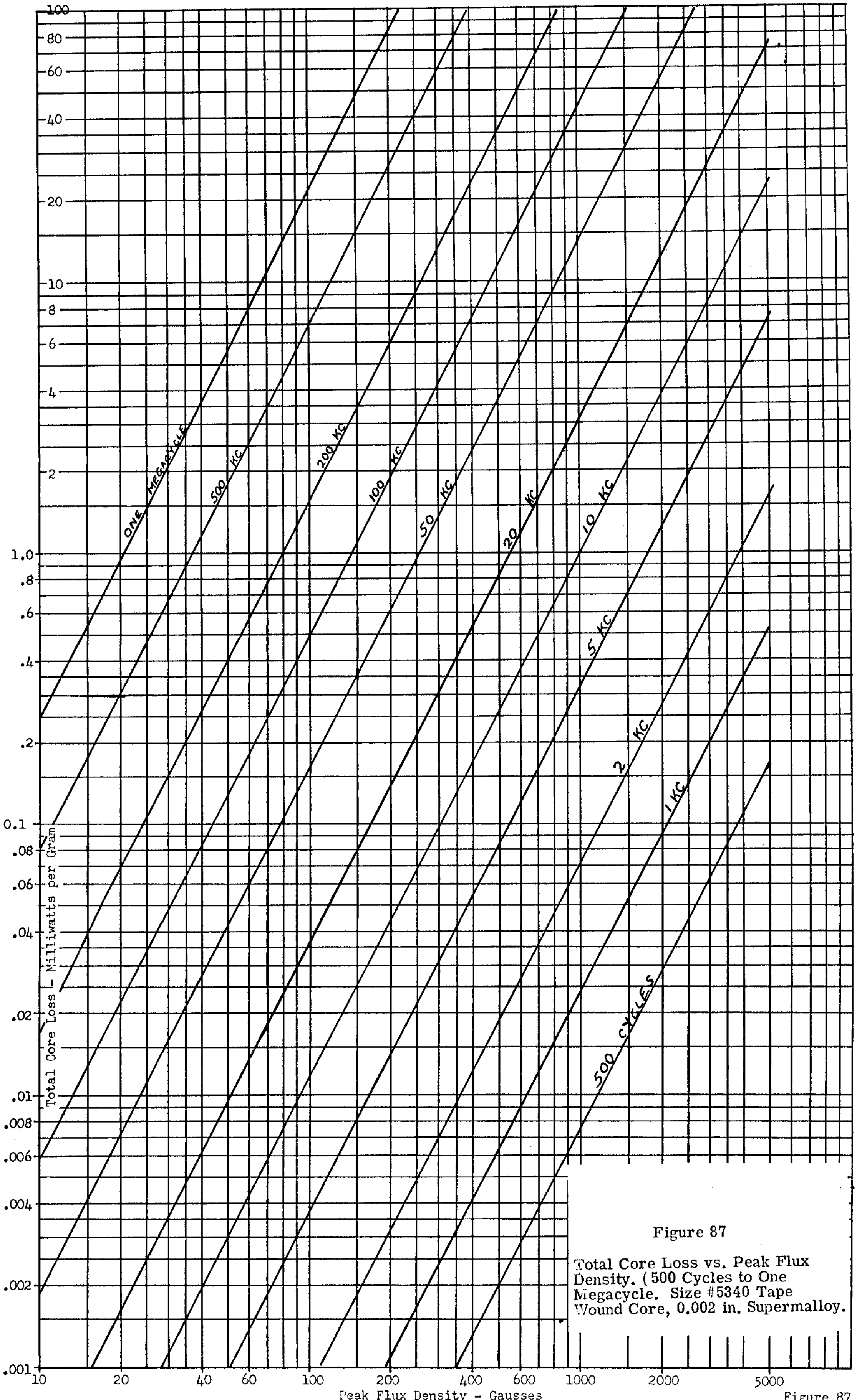


Figure 87

Total Core Loss vs. Peak Flux Density. (500 Cycles to One Megacycle. Size #5340 Tape Wound Core, 0.002 in. Supermalloy.

Figure 87

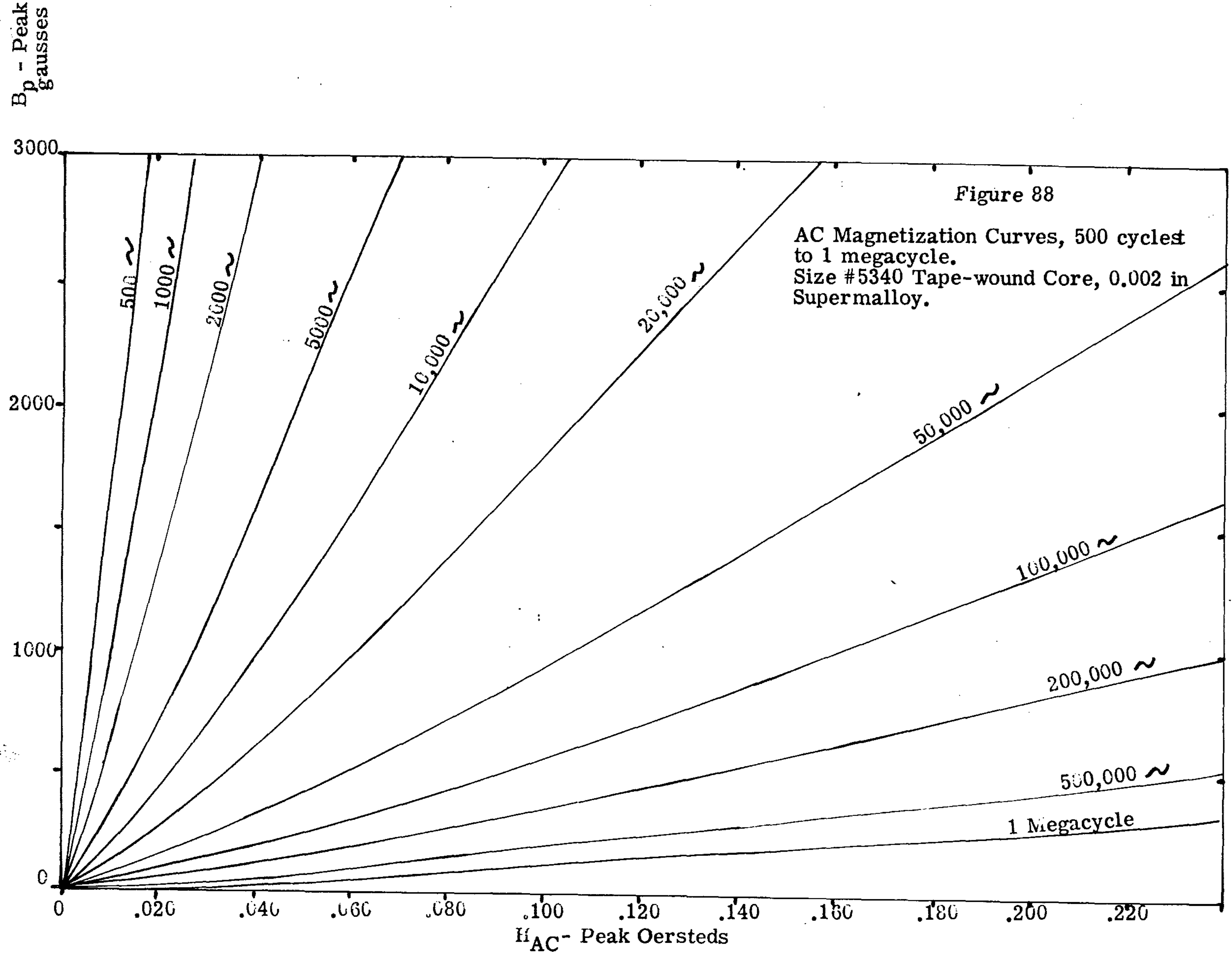


Figure 88

AC Magnetization Curves, 500 cycles to 1 megacycle.
Size #5340 Tape-wound Core, 0.002 in Supermalloy.

Figure 89

Low Density AC Magnetization Curves
500 Cycles to 1 Megacycle, Size #5340
Tape-wound Core - 0.002 in. Supermalloy

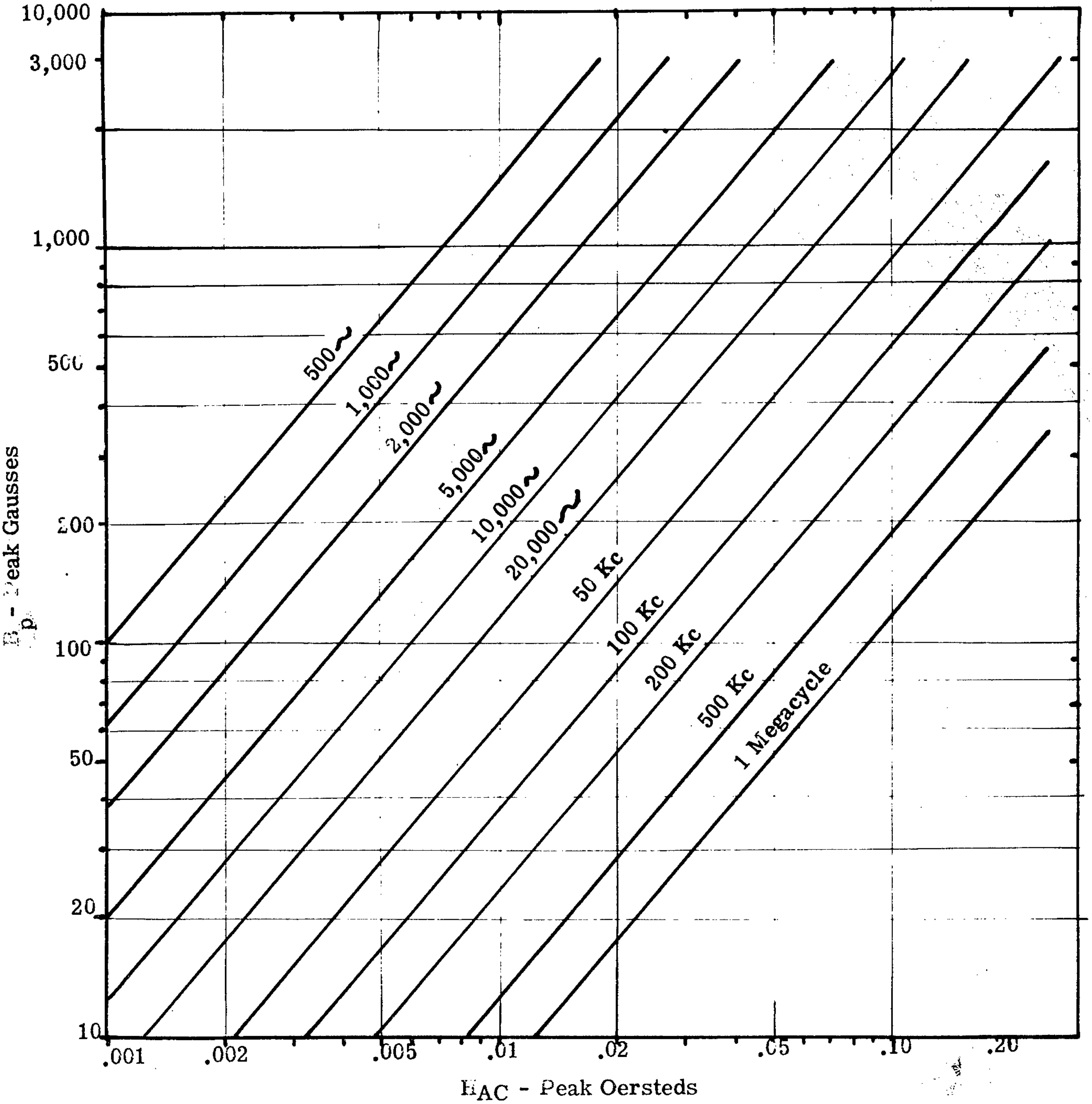
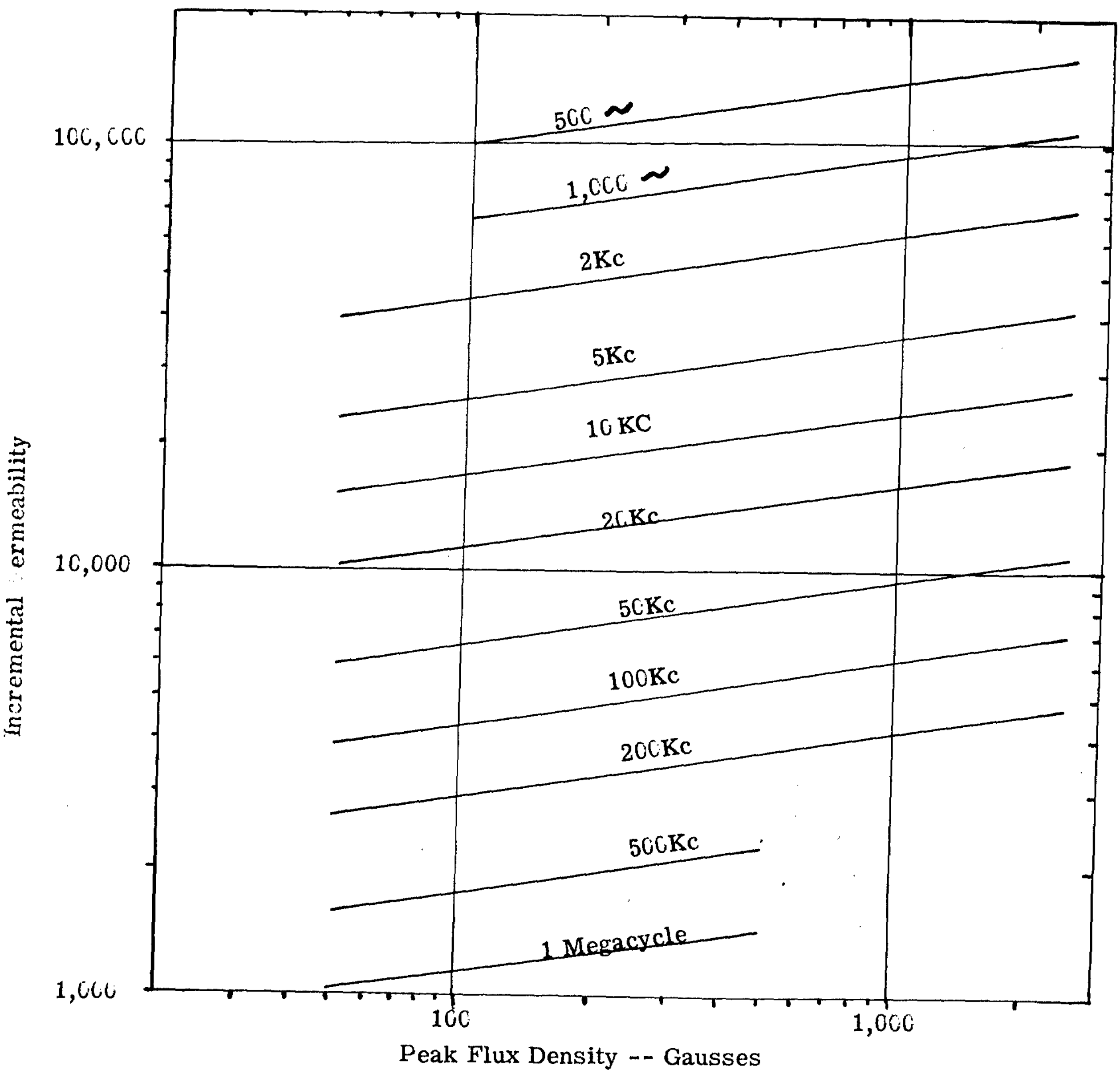


Figure 90

Incremental Permeability vs Peak Flux Density
Zero Control DC Magnetizing Force
Size #5340 Tape-wound Core - 0.002 in Supermalloy
500 Gausses Peak Flux Densities, 500 cycles to 1 Megacycle.



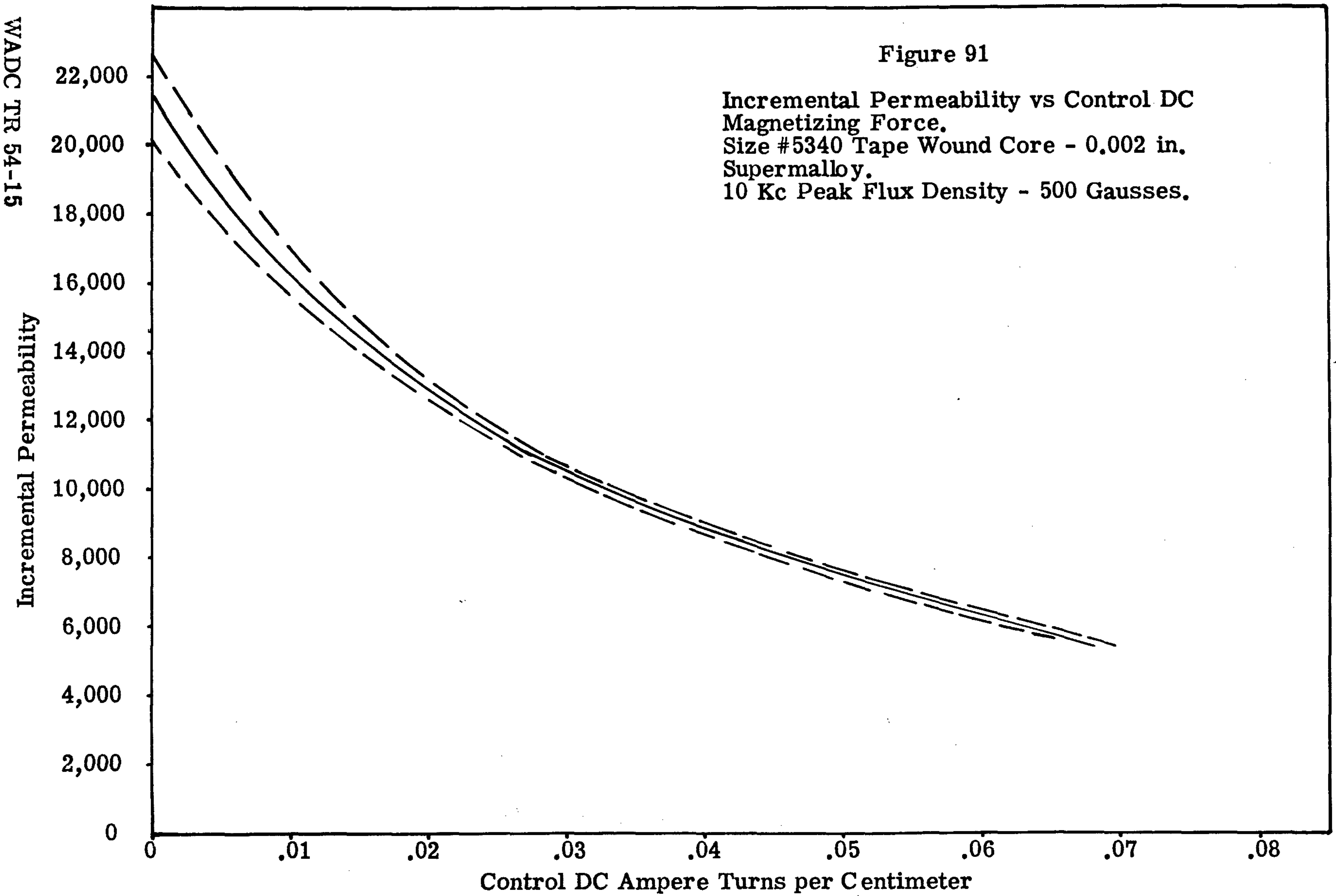


Figure 91

Incremental Permeability vs Control DC Magnetizing Force.
Size #5340 Tape Wound Core - 0.002 in. Supermalloy.
10 Kc Peak Flux Density - 500 Gausses.

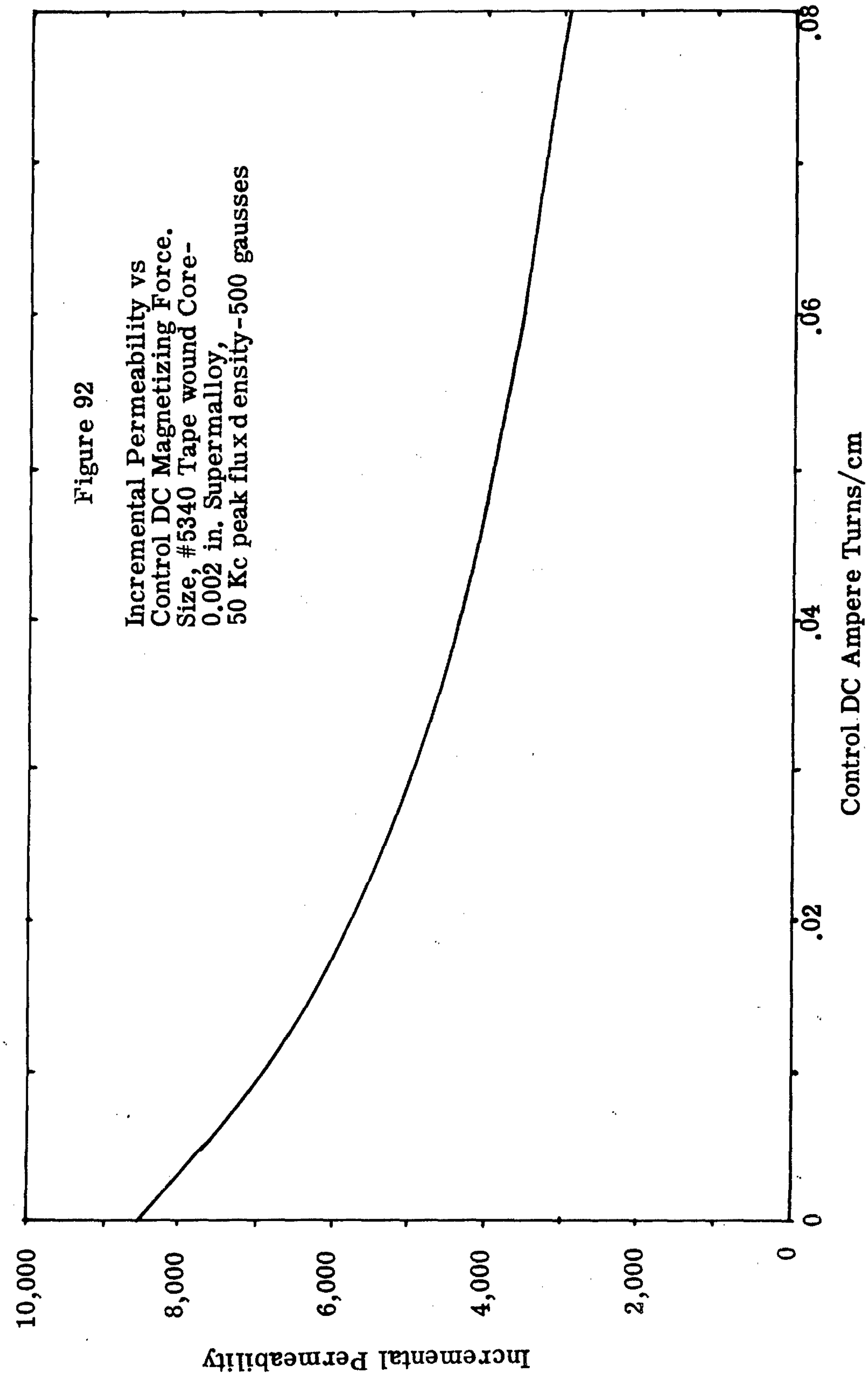


Figure 92

Incremental Permeability vs Control DC Magnetizing Force. Size, #5340 Tape wound Core-0.002 in. Supermalloy, 50 Kc peak flux density-500 gausses

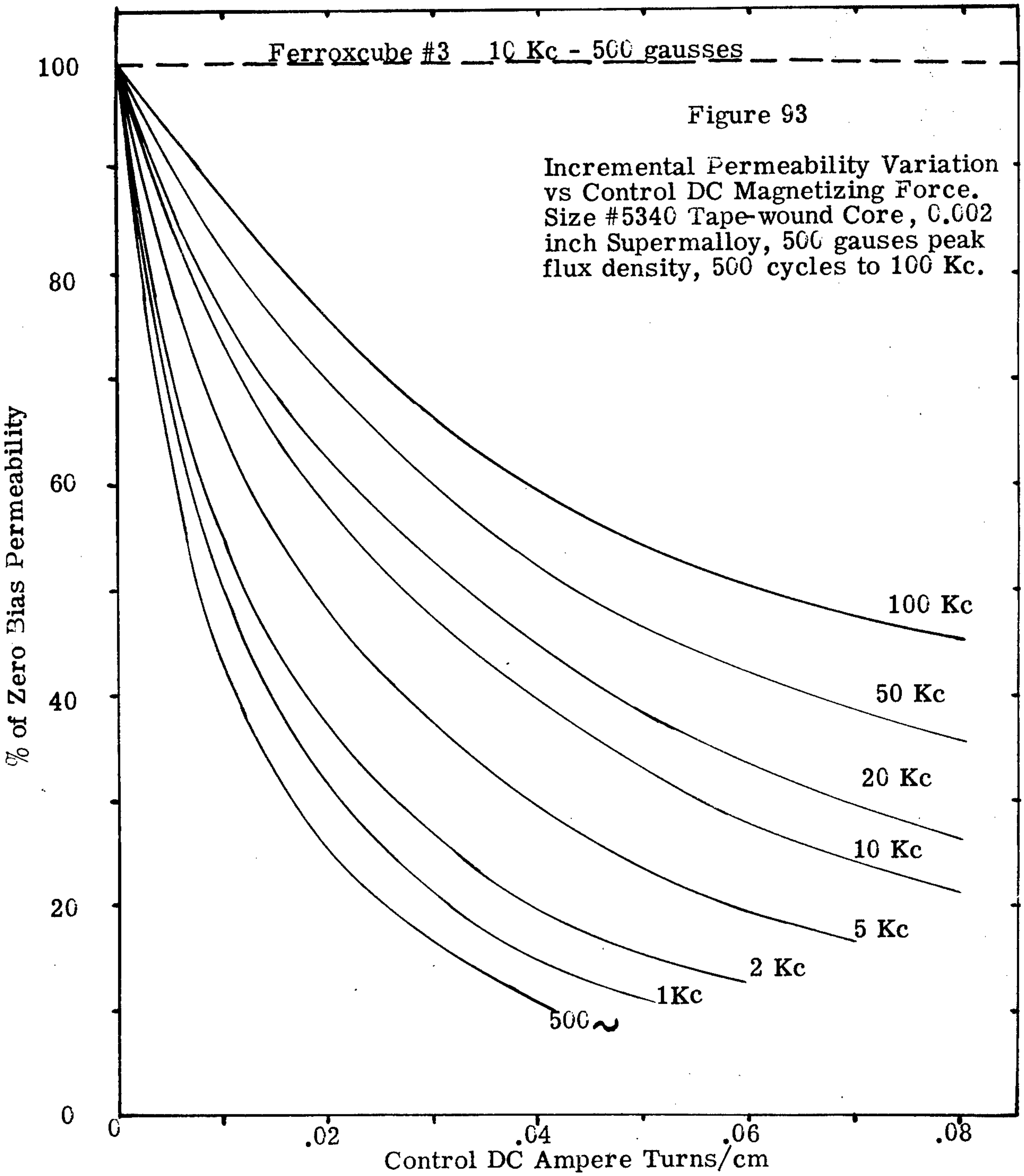
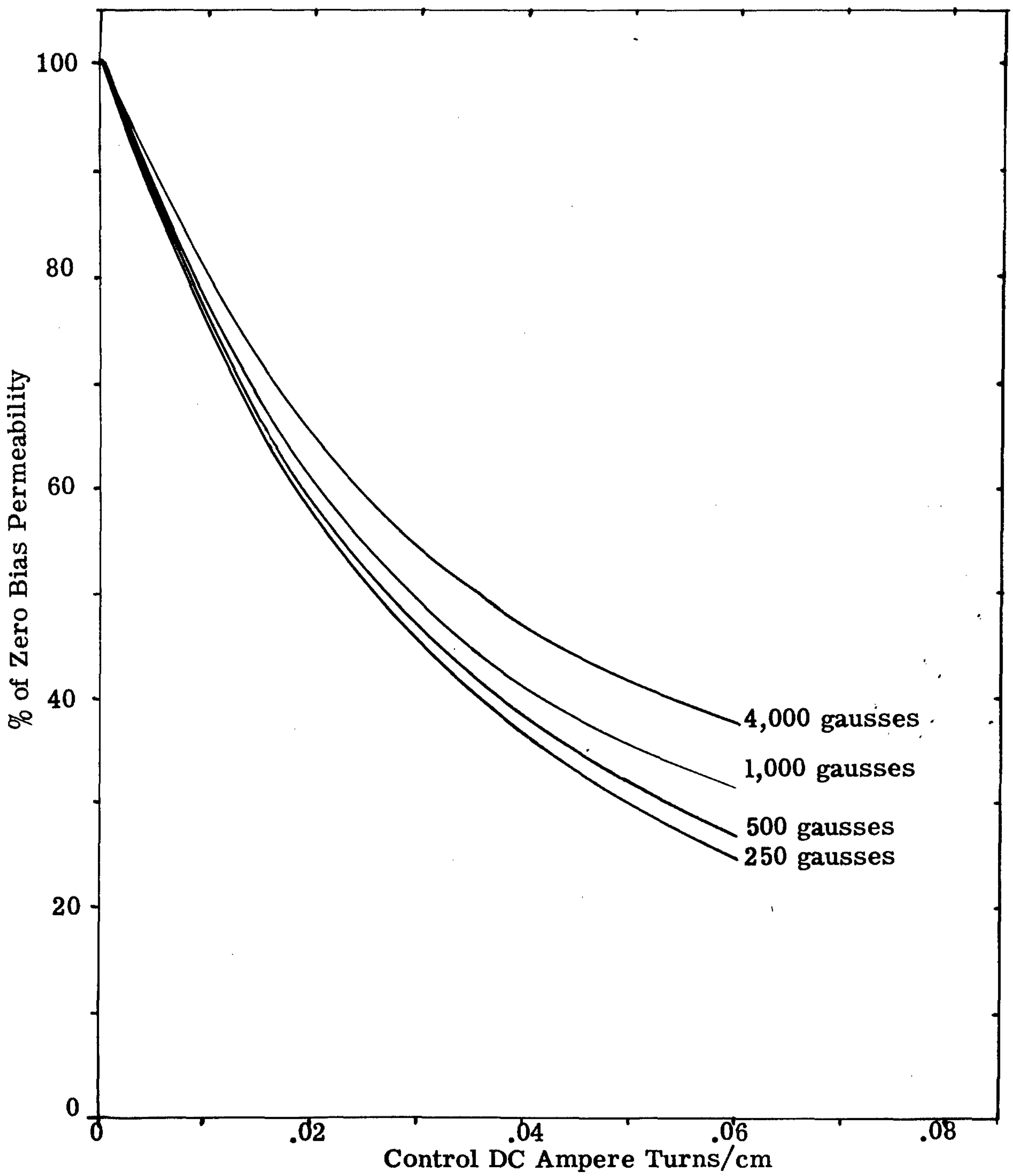


Figure 93

Incremental Permeability Variation vs Control DC Magnetizing Force. Size #5340 Tape-wound Core, 0.002 inch Supermalloy, 500 gauses peak flux density, 500 cycles to 100 Kc.

Figure 94

Incremental Permeability Variation vs Control DC Magnetizing Force Size #5340 Tape-wound Core - 0.002 in, Supermalloy. 250 to 4,000 Gausses Peak flux density, 10 Kc.



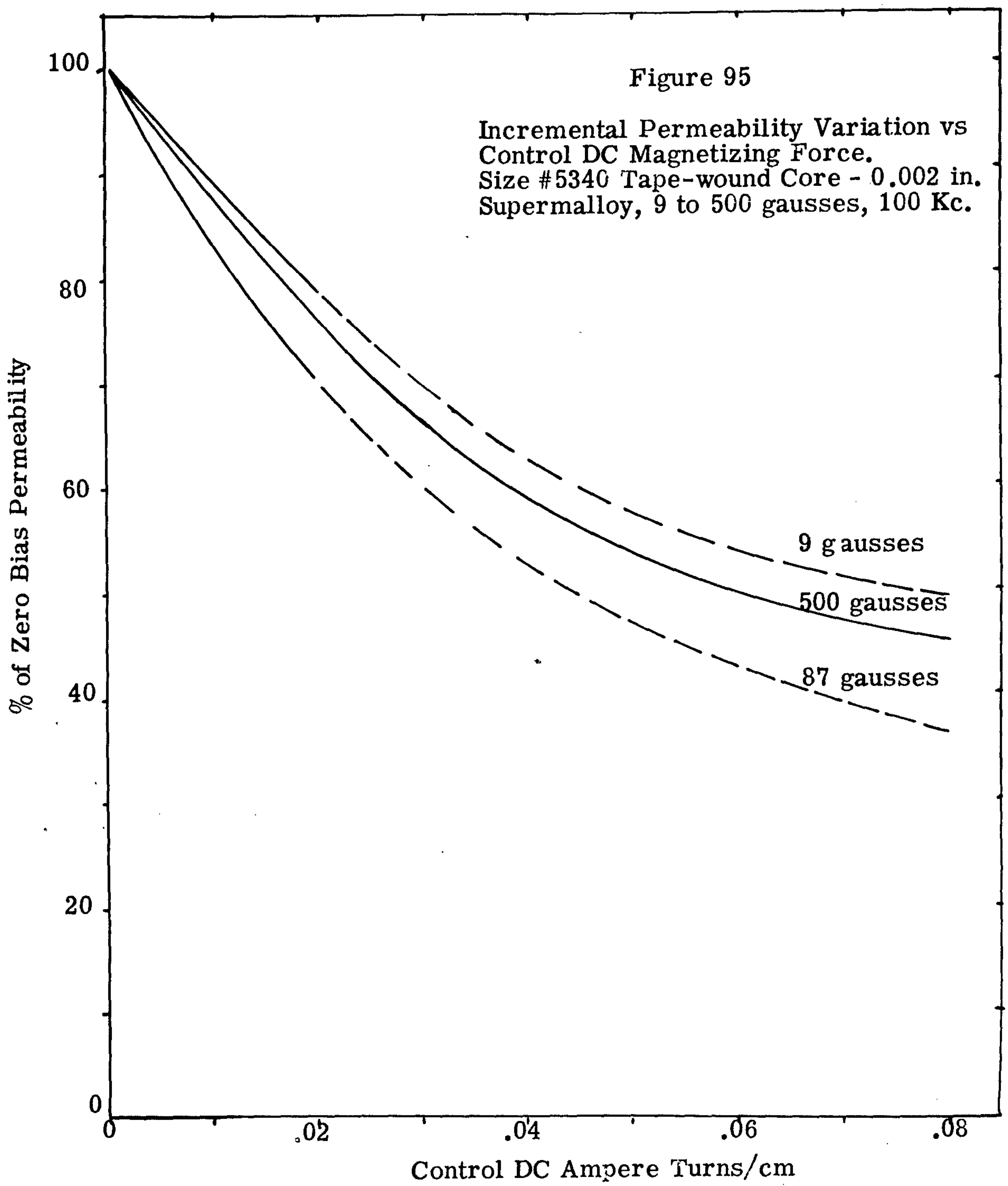


Figure 95
Incremental Permeability Variation vs
Control DC Magnetizing Force.
Size #5340 Tape-wound Core - 0.002 in.
Supermalloy, 9 to 500 gausses, 100 Kc.
100
80
60
40
20
0
% of Zero Bias Permeability
9 gausses
500 gausses
87 gausses
0
.02
.04
.06
.08
Control DC Ampere Turns/cm

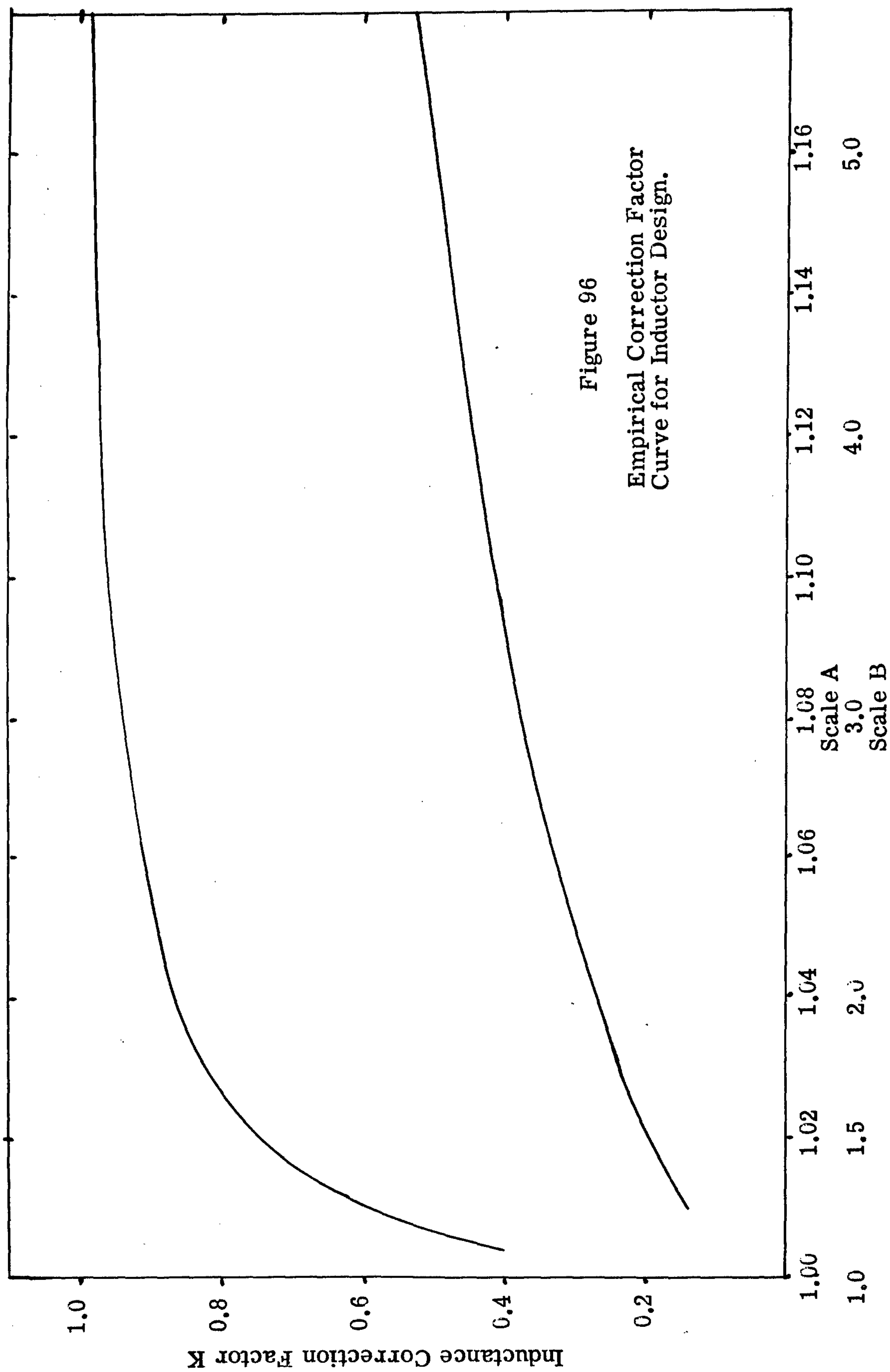
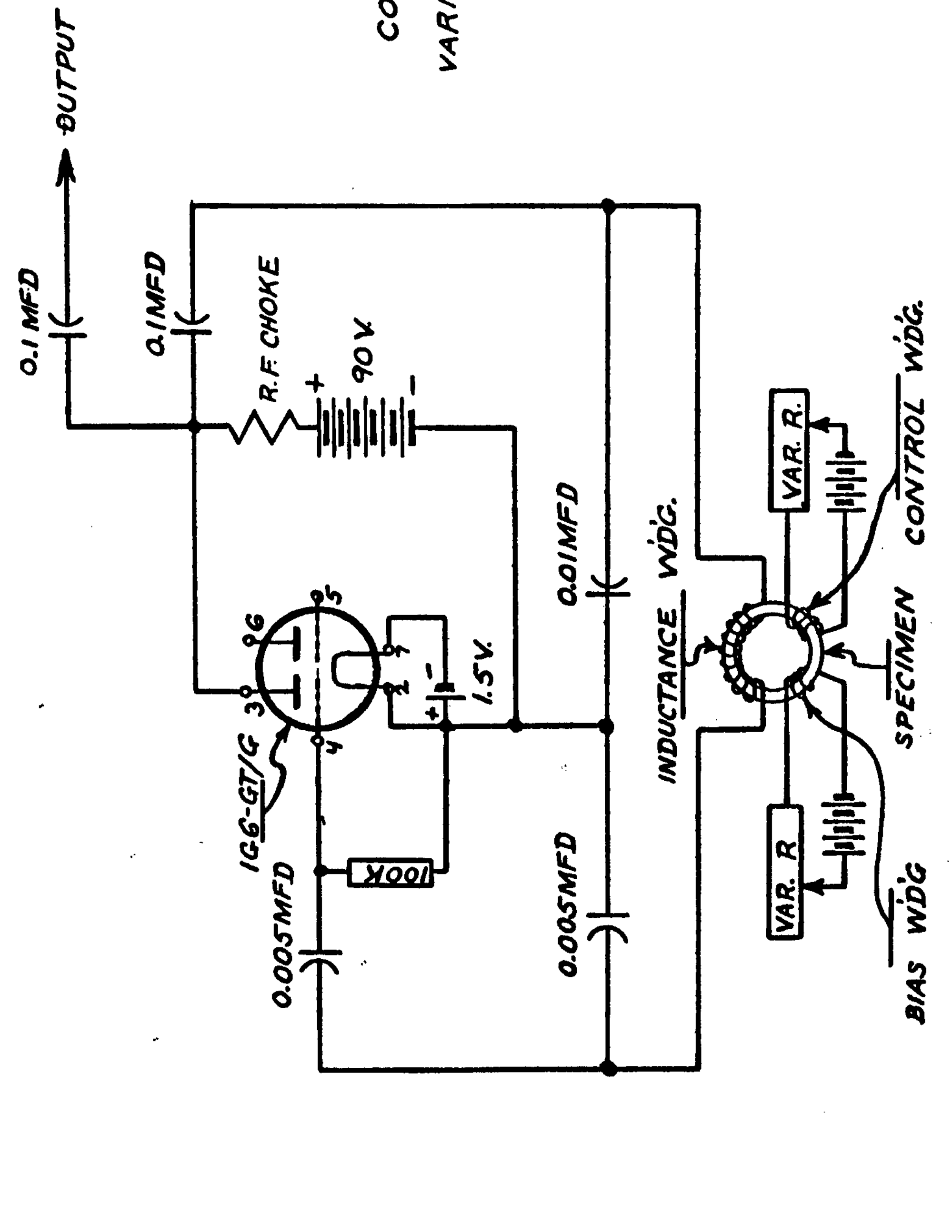
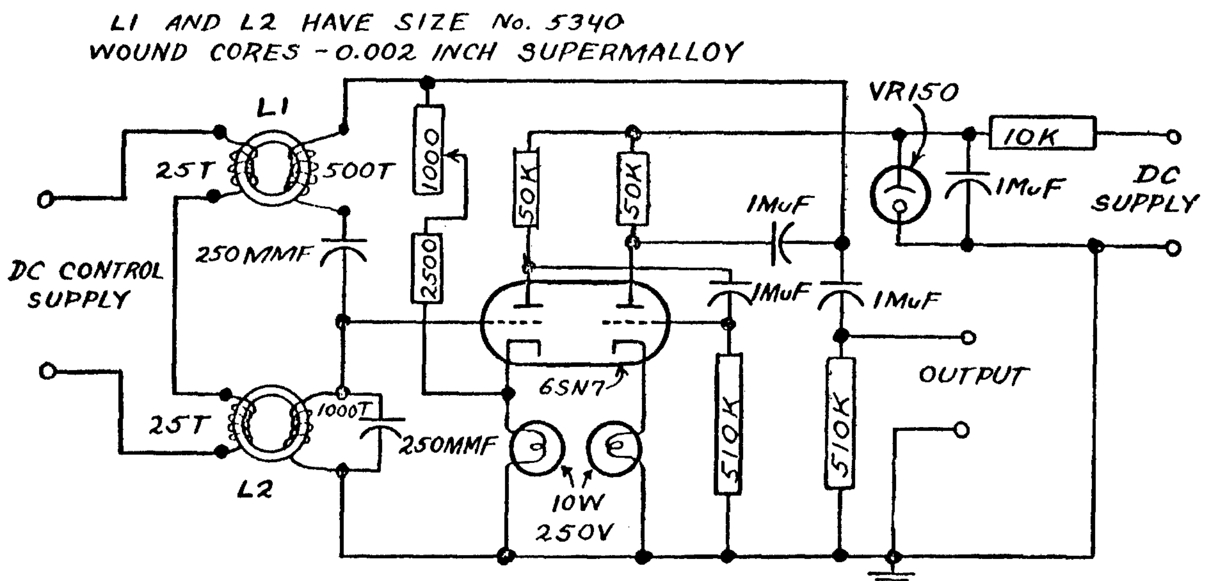


Figure 96

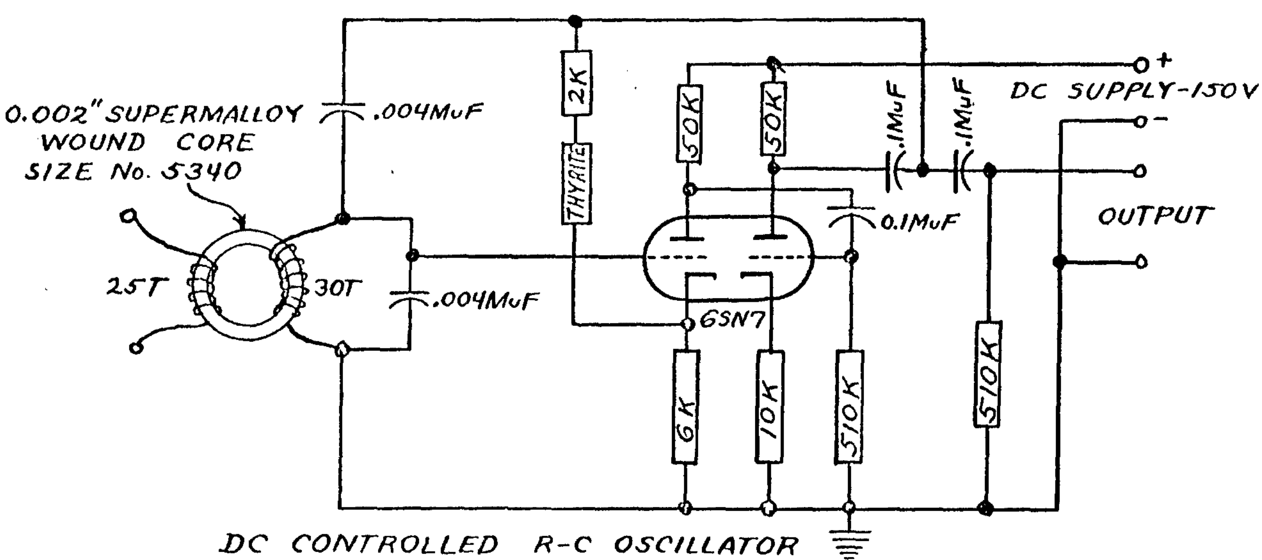
Empirical Correction Factor Curve for Inductor Design.

COLPITTS OSCILLATOR
WITH
VARIABLE INDUCTANCE
FIG. 97





DC CONTROLLED R-C OSCILLATOR
FIGURE 98



DC CONTROLLED R-C OSCILLATOR
FIGURE 99

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APPENDIX A

TESTING CIRCUITS

Section I - Dynamic Hysteresis Loops

The test circuit that is ordinarily used in the General Engineering Laboratory for producing dynamic hysteresis loops was used in this investigation, Figure 100.

Essentially, this circuit amplifies a very small voltage drop across R_1, and applies it to the horizontal input terminals of a cathode-ray oscilloscope to produce a horizontal beam deflection proportional to the magnetizing force produced by the exciting winding on the specimen. The voltage induced in the potential winding on the specimen is integrated, amplified and applied to the vertical input of the oscilloscope to produce a vertical beam deflection proportional to the flux density in the specimen. The resulting figure is a dynamic hysteresis loop of the specimen material. By using an oscilloscope having an illuminated graticule, and by properly adjusting the gain controls, the sizes of the loops can be adjusted so they will have even scales of gausses and oersteds, and then photographed.

A discussion of this method of producing dynamic hysteresis loops is given by H. W. Lord in his article, "Dynamic Hysteresis Loop Measuring Equipment," in Electrical Engineering, June 1952. The following additional comments may be helpful.

The matching transformer, T, may be used if required for matching the impedance of the exciting winding on the specimen to the amplifier output impedance. This may be a radio driver or filament transformer, or any other that is found to be suitable.

The resistance, R_1, should be noninductive, and it should have a low value so the voltage drop across it will be negligible in comparison with the voltage applied to the exciting winding. This resistor should be made of a short piece of resistance wire, wound noninductively, so the ratio of its resistance to its reactance at the operating frequency will be high. This is necessary to avoid distortion of the hysteresis loop due to phase shift.

The voltmeter, V_k, is used to determine the peak flux density in the specimen. It should be calibrated to read 1.11 times the average value of a complex wave, and it should be a vacuum tube voltmeter having very high input impedance so it will not load the potential winding. The Hewlett Packard, Type 400C, or equivalent, is recommended.

The capacitor, C, and the resistor, R_2, in combination, form the integrator. This combination is adequate for loop comparisons as used in this investigation. The value of R_2 should also be high to avoid loading the potential winding. Its value may be about a megohm, but it is somewhat dependent on the

frequency and voltage in use. The capacitor, C, should be as large as possible without reducing the voltage drop across it to a value too small to be useful. In any case, the reactance of the capacitor at the operating frequency should be less than ten per cent of the resistance of R_1, and only about one per cent if sufficient amplification is available to compensate for an integrator attenuation of 100:1.

Amplifiers A and C are low level units designed to operate with input signals in the millivolt range. They have adjustable gain, and their maximum output voltage is one volt. They must have flat response and very low phase shift over a very wide frequency range. The ones used in this investigation were Tektronix Wide Band Preamplifiers, Type 121.

Amplifier B is used to provide a deflecting signal to the horizontal plates of the oscilloscope, since the one used did not have its own internal horizontal amplifier. The Tektronix Direct Coupled Amplifier Type 112 was used at this point.

The cathode-ray oscilloscope used in this setup must also have very low phase shift and flat response over a wide frequency range. The Tektronix Type 514D was used in this investigation and found to be adequate.

The control circuit was provided to make it possible to take minor loops. The value of R_3 was 50,000 ohms, and that of R_v was variable from zero to 300,000 ohms. The DC source was adjustable and provided from 200 to 320 volts. The DC milliammeter read 7.5 milliamperes, full scale. The use of the large values of resistance in the control circuit avoided the effects of transformer action between the exciting and control windings.

A Polaroid Land Camera was used to photograph the loops that were produced on the oscilloscope screen.

The calibration of the equipment was done in the manner described below. The specimen was carefully removed from its protective Nylon case and weighed, The mean diameter was also measured and the specimen then carefully replaced in the Nylon case. The length of the magnetic circuit, ℓ, was calculated by the equation:

$$\ell = \pi d \text{ centimeters} \qquad 1.$$

where d = mean core diameter in cm.

The effective cross sectional area was calculated by means of the equation:

$$A = \frac{G}{D\ell} \text{ square centimeters} \qquad 2.$$

where G = specimen weight in grams

and D = specimen density

The windings were then placed on the Nylon container; first, the exciting winding, then the potential winding, and last, the control winding. The desired operating voltage, frequency and approximate peak flux density at which the loop was to be produced were assumed and the required number of exciting turns calculated by means of the equation:

$$N_L = \frac{10^8 V_L}{4.44 B_p A f} \text{ turns} \qquad 3.$$

where: V_L = RMS excitation voltage
B_p = peak flux density, gausses
f = test frequency, cycles per second
A = magnetic area, square centimeters

A potential winding having approximately half or two-thirds as many turns as the exciting winding was then put in place, and the remainder of the available space filled with a control winding. In the cases of the small closed cores, wire size was not important, but the smallest that was used for exciting and potential windings was 0.005 inches, and the largest was 0.040 inches for the control windings.

A peak flux density of 5000 or 10,000 gausses (or some other even number) was then assumed, and the equation 3 was used to calculate the voltage that would be induced in the potential winding, and would thus be read on the voltmeter V_k, at this peak flux density.

A selected value was then assumed for the tip magnetizing force to be used, and this was designated as H. The RMS value of the sinusoidal exciting current that would be required to produce the assumed tip magnetizing force, H, if it were flowing in the exciting winding, was then calculated by use of the following equation:

$$I = \frac{H \ell}{.4\pi N_L \sqrt{2}} \text{ amperes (RMS)} \qquad 4.$$

where: H = peak magnetizing force (assumed)
N_L = turns calculated from (3)
ℓ = length of magnetic circuit from (1)

The bias magnetizing force per milliampere of DC was calculated from the equation:

$$H_{DC} = \frac{N_C I_{DC}}{\ell} \text{ oersteds} \qquad 5.$$

I_{DC} = 0.001 amperes, DC
N_C = turns in control winding

After the calculations were completed, the specimen was connected in the test circuit shown in Figure 100. With the switch S in the CAL position, the supply voltage was adjusted until the value of current that had been calculated

as being necessary to produce the desired tip magnetizing force was indicated on the RMS reading AC milliammeter, M_1. (This current was sinusoidal, and, therefore, had the peak to RMS ratio of 1.41:1 as used in the calculations, since it was flowing in a unity power factor circuit consisting of R_1 and R_4 and the milliammeter.) With the "B" amplifier gain reduced so only a horizontal trace appeared, the gain of the "H" amplifiers was adjusted until the length of the "H" trace was as desired for an even scale. The switch S was then operated to the TEST position, and with the "H" amplifier gains unchanged, the source was readjusted until the horizontal trace again became the same length as before. Although the magnetizing current wave shape was now probably no longer sinusoidal, the tip values of "H" were the same as the previously assumed value.

The "B" amplifier gain was then adjusted by changing the supply until the voltmeter V_k read the previously calculated value for the assumed peak flux density. The "B" amplifier gains were then adjusted so the vertical deflection fit the selected scale. Calibration was now complete, and with the amplifier gains unchanged from these settings, the source could be varied as desired, and values of B and H read directly from the pattern on the face of the oscilloscope. An experienced operator can very rapidly make the calculations and adjustments described.

Section II - Core Loss Measurements with the Light Beam Wattmeter

The circuit used for making core loss measurements, directly, with the dynamometer type wattmeter is shown in Figure 101.

This circuit needs but little explanation. The reading of the vacuum tube voltmeter V_k is used to calculate the peak flux density, using the equation:

$$B_p = \frac{10^8 V_K}{4.44 A N_K f} \text{ gausses} \qquad 6.$$

V_K = potential winding volts (RMS)

N_K = potential winding turns

The magnetic area of the core should be determined from the weight of the specimen and the length of the magnetic circuit, as described in Section I.

The cathode-ray oscilloscope is used as shown to be certain that the wave form of the flux in the specimen is sinusoidal.

The wattmeter used in this circuit was the General Electric Light Beam Wattmeter, Catalog No. 9103909G23, which has been developed for this type of work. It is a multiple range instrument having both one and two ampere current windings, and several potential coils rated from 15 to 300 volts. It provides power ranges from one watt full scale to 40 watts full scale at power factors as low as 8%.

Its normal frequency range is from 25 to 1000 cycles per second, but by special calibration, its useful frequency range can be extended to at least 10 kilocycles.

This instrument is described more completely in General Electric Bulletin GEC-252.

The wattmeter is connected in Figure 101 so that its reading includes the total core loss in the specimen, the copper loss in the potential winding, the copper loss in the wattmeter potential coil and the voltmeter and oscilloscope input losses. The latter two should be negligible, as the input resistances of these instruments are very high. (It is recommended that the Hewlett Packard Type 400C vacuum type voltmeter should be used for measuring V_K.) Corrections can be made for the potential winding and wattmeter potential coil copper losses.

Since the wattmeter potential coil is not connected across the exciting winding, the wattmeter reading must be multiplied by the ratio of the number of turns in the exciting winding to the number of turns in the potential winding, to secure the total power input to the inductor.

Section III - Core Loss Measurements with the Vector Diagram Method

The vector diagram method of making core loss measurements has been used in the General Engineering Laboratory for several years. It is especially useful when the frequency at which measurements are to be made is beyond the range of conventional wattmeters, or when measurements are to be made at very low power levels.

The elementary circuit used in the vector diagram method is shown in Figure 102. Measurements can be made by this method with good accuracy when the four indicated voltages are maintained sinusoidal. This is ordinarily not difficult when the specimen is magnetized to values of peak flux density below the knee of the magnetization curve. In this investigation, a large portion of the data were secured in this region and at very low power levels, so this technique was ideal.

Referring to Figure 102, it is obvious that the voltage V_S is equal to the vector sum of the two voltages, V_C and V_L. With the output of the adjustable frequency power source adjusted to the selected test frequency and voltage level to produce the desired peak flux density in the specimen, the three indicated voltages are measured with a vacuum tube voltmeter. A vector diagram is constructed using the scaler values of these voltages, as shown in the Figure 106.

As a matter of convenience, the diagram should be drawn on graph paper. A reference vector, I_{AC}, is drawn (not to scale) from the point O. A convenient scale for the voltage vectors is selected, and the vector Vc is drawn from point O, lagging the current vector by 90 degrees. The two arcs, V_S and V_L, are then drawn, using the same voltage scale as was used for V_C. A pair of dividers is

adjusted to the length of the vector V_c, and by trial, two points, A and B, one on each of the arcs and separated by the length of V_c, are located so that a line joining them will be parallel to the vector V_c. This is not at all difficult if rectangular coordinate paper has been used, as the current vector can be laid out along a horizontal line, and the voltage vector V_c along a vertical line. All vertical lines are then parallel to this latter vector, and the construction is simplified. The two points, A and B, that have been located on the two arcs are the ends of the V_L and V_s vectors, as shown, and these vectors can then be drawn from the point O. A line drawn through the points A and B is perpendicular to the current vector and locates the reactance component, E_X of V_L. The resistance component of V_L is the vector from point O along the current vector to the end of E_R and is labeled E_R. Figure 103 was drawn to show the diagram when the impedance of the inductor was greater than the reactance of the capacitor. Figure 104 shows the diagram when a smaller capacitor was used, and the impedance of the inductor was less than that of the capacitor.

The various quantities that can be determined from the vector diagram, such as power loss in the inductor, Q of the inductor, inductive reactance, inductance, etc., are shown in Figure 106.

It is obvious that the vector method is convenient and accurate for measuring, under somewhat adverse conditions, quantities associated with inductors.

The practical test circuit that was actually used is shown in Figure 105. It will be noted that a very small resistor, R, has been added, and a cathode-ray oscilloscope connected to show the voltage drop across this resistor. This voltage drop is proportional to the magnetizing current, so distortion can be seen if it occurs, and tests at higher peak flux densities can be avoided.

The circuit for applying a DC bias magnetic field is also included in this setup.

Four voltmeters are shown, for convenience, although by using appropriate switching, the required voltage readings can be secured with one or two instruments.

The value of R is made small (five ohms was used), so the voltage, V_i, will be negligible (a few millivolts), compared with V_c, and the V_c reading, which includes V_i, does not need to be corrected.

The peak flux density is calculated from the reading of the V_K voltmeter, and V_L is also secured from this reading by multiplying it by the turns ratio.

The Hewlett Packard Type 400C vacuum tube voltmeters were used in this setup. Since one terminal of these instruments is normally operated at ground potential, the particular arrangement shown permits this operation without encountering grounding difficulties.

Section IV - Transverse Biasing Fields - Test Equipment

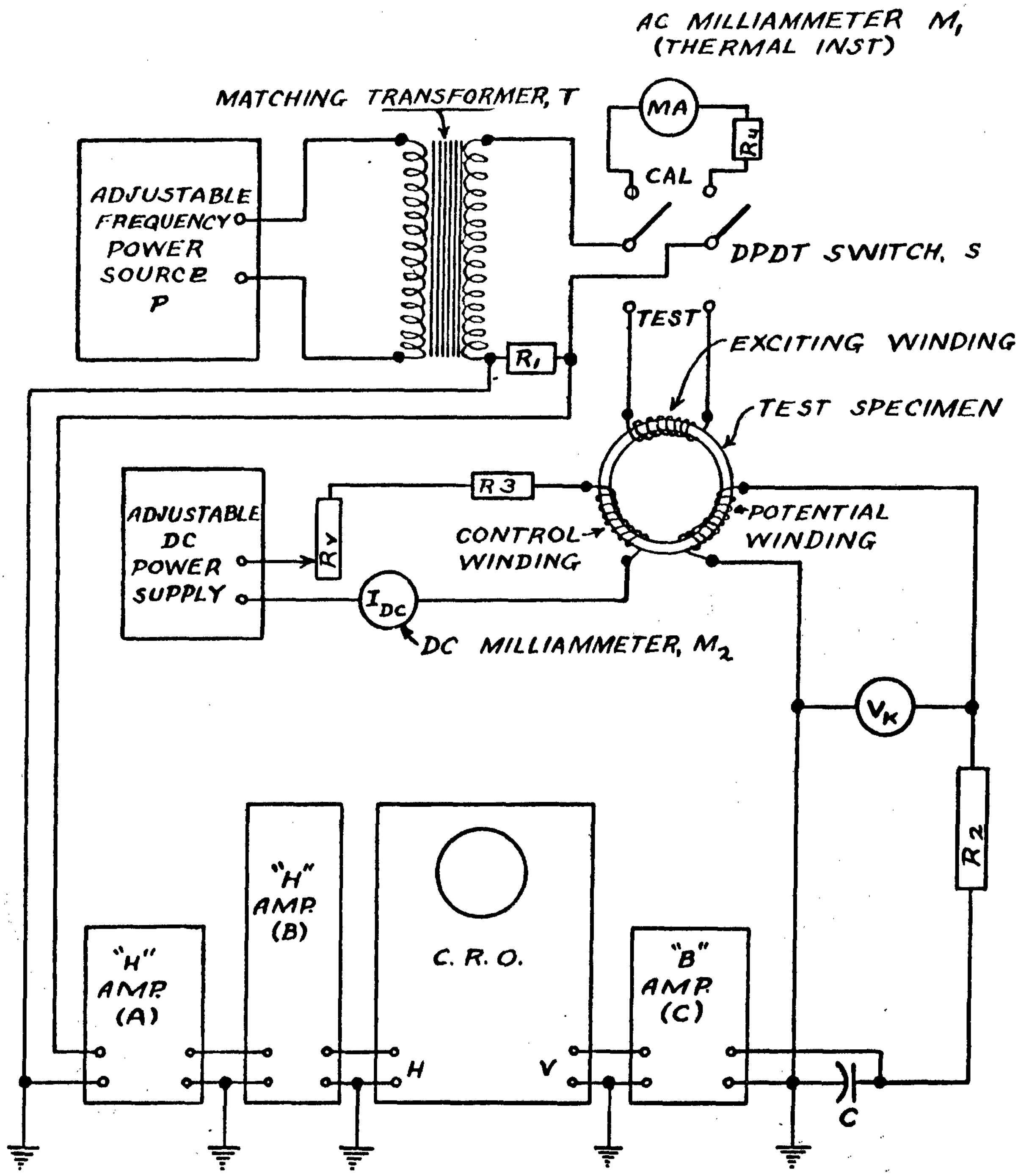
The equipment used to determine the effect of a transverse biasing field is shown in the functional sketch of Figure 107.

A General Electric Company magnetizer, Catalog Number 5120876G1, was equipped with two parallel pole pieces of magnetic material placed about an inch apart, as shown. The specimen to be tested was placed between the flat pole pieces with a nonmagnetic spacer block. A General Electric Gauss Meter was placed in a hole in the spacer block, so the field intensity could be read. A 500 cycle voltage was applied to the winding on the specimen, in series with a 1000 ohm resistor, as shown in the diagram.

With no current in the magnetizer windings, the voltage drop across the resistor was read with a vacuum tube voltmeter. The magnetizer was then energized, and the field, as indicated by the gauss meter, increased to a value as high as 700 oersteds. The current increase in the winding on the specimen was negligible with the specimen carefully placed in the test fixture so the field was essentially transverse. When a small wedge was placed under one edge of the specimen, so it was tipped in the field, the current increased rapidly as the magnetic field strength was increased.

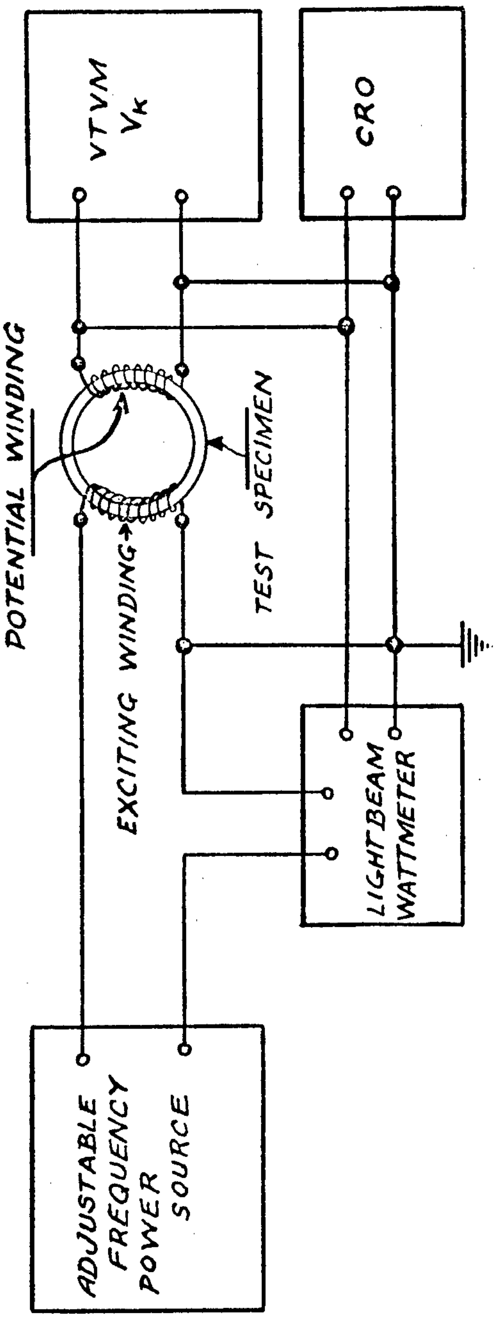
The specimen was removed from the test fixture, held in the earth's field and rotated at all angles, with no measurable alteration of the 500 cycle current in the resistor.

TEST CIRCUIT FOR PRODUCING DYNAMIC HYSTERESIS LOOPS



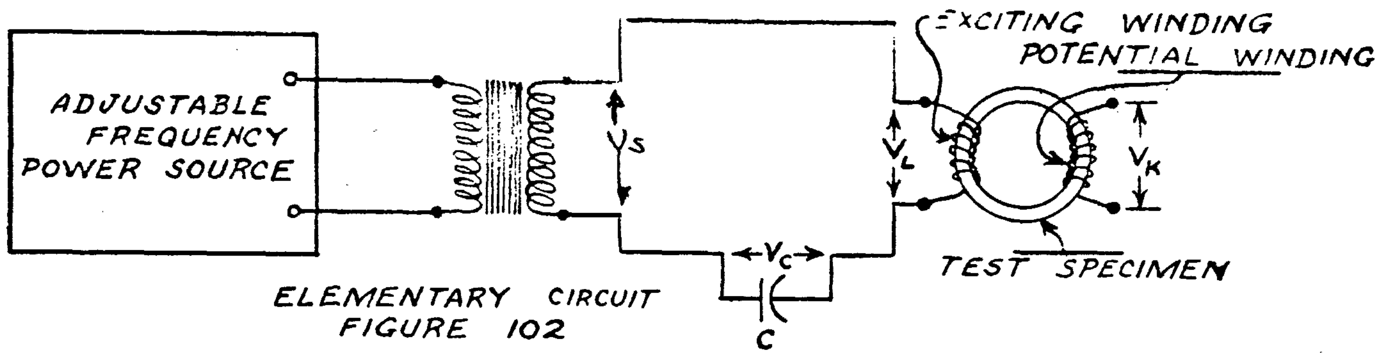
AMPLIFIER (A) - TEKTRONIX TYPE 121 OR EQUIVALENT
AMPLIFIER (B) - TEKTRONIX TYPE 112 OR EQUIVALENT
AMPLIFIER (C) - SAME AS AMPLIFIER (A)
C. R. O. - TEKTRONIX TYPE 514D OR EQUIVALENT

FIGURE 100

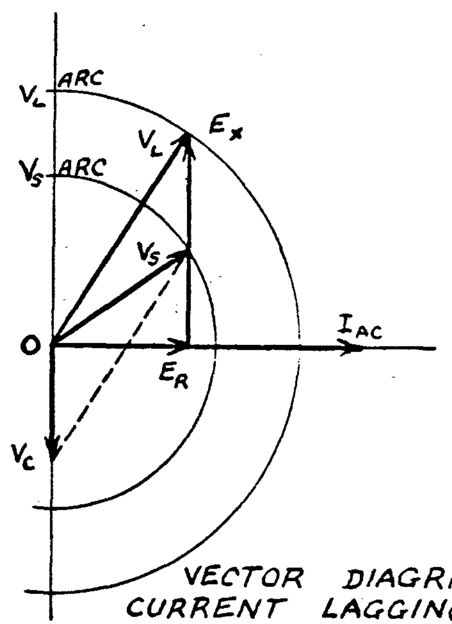


TEST CIRCUIT FOR CORE LOSS MEASUREMENTS WITH THE LIGHT BEAM WATTMETER
FIGURE 101.

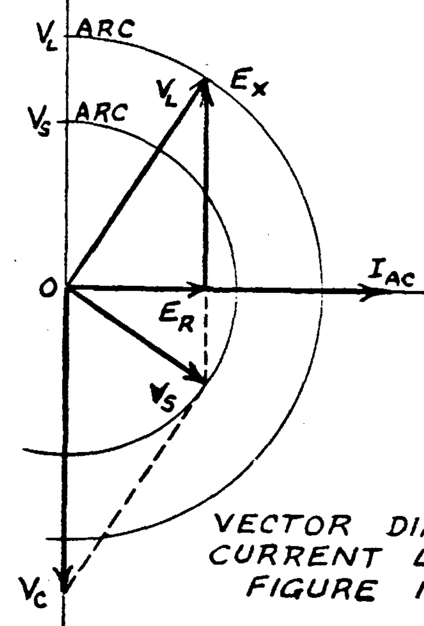
MAGNETIC MEASUREMENTS
BY THE
VECTOR DIAGRAM METHOD



ELEMENTARY CIRCUIT
FIGURE 102

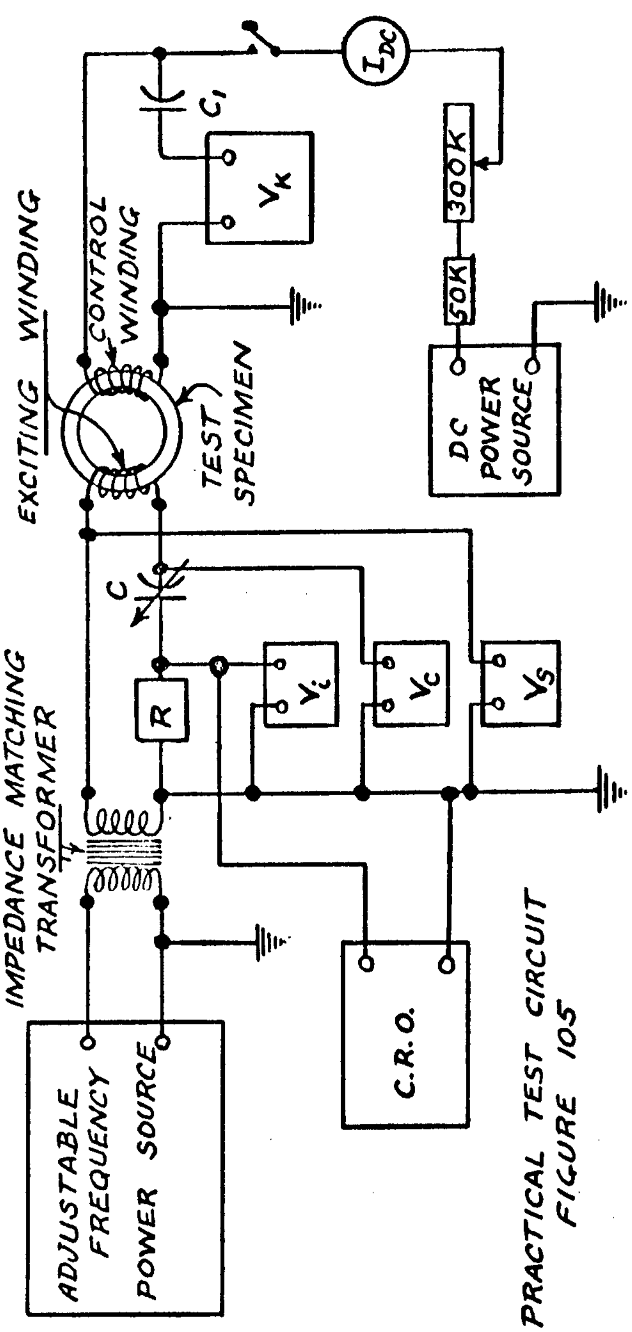


VECTOR DIAGRAM
CURRENT LAGGING
FIGURE 103



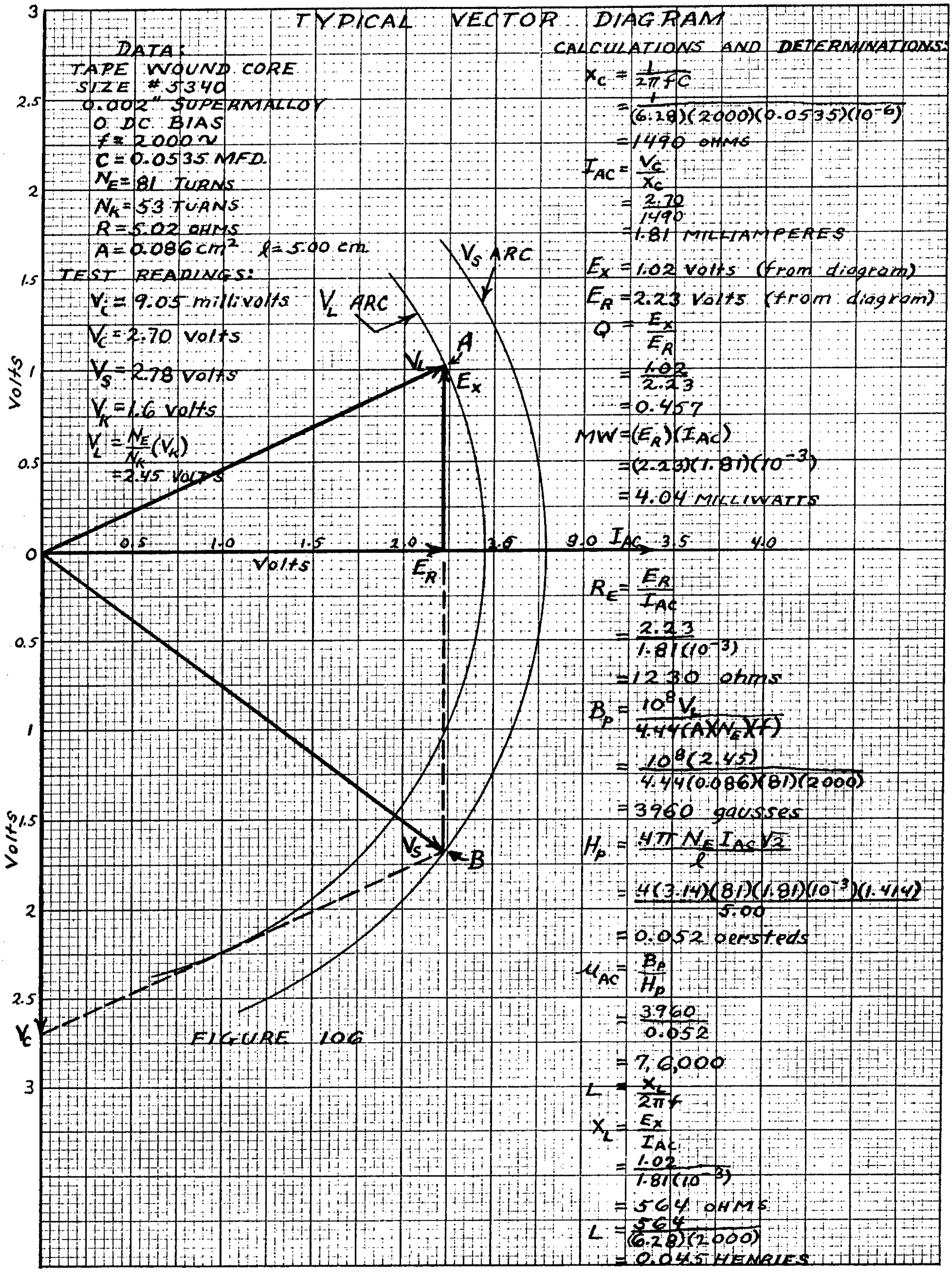
VECTOR DIAGRAM
CURRENT LEADING
FIGURE 104

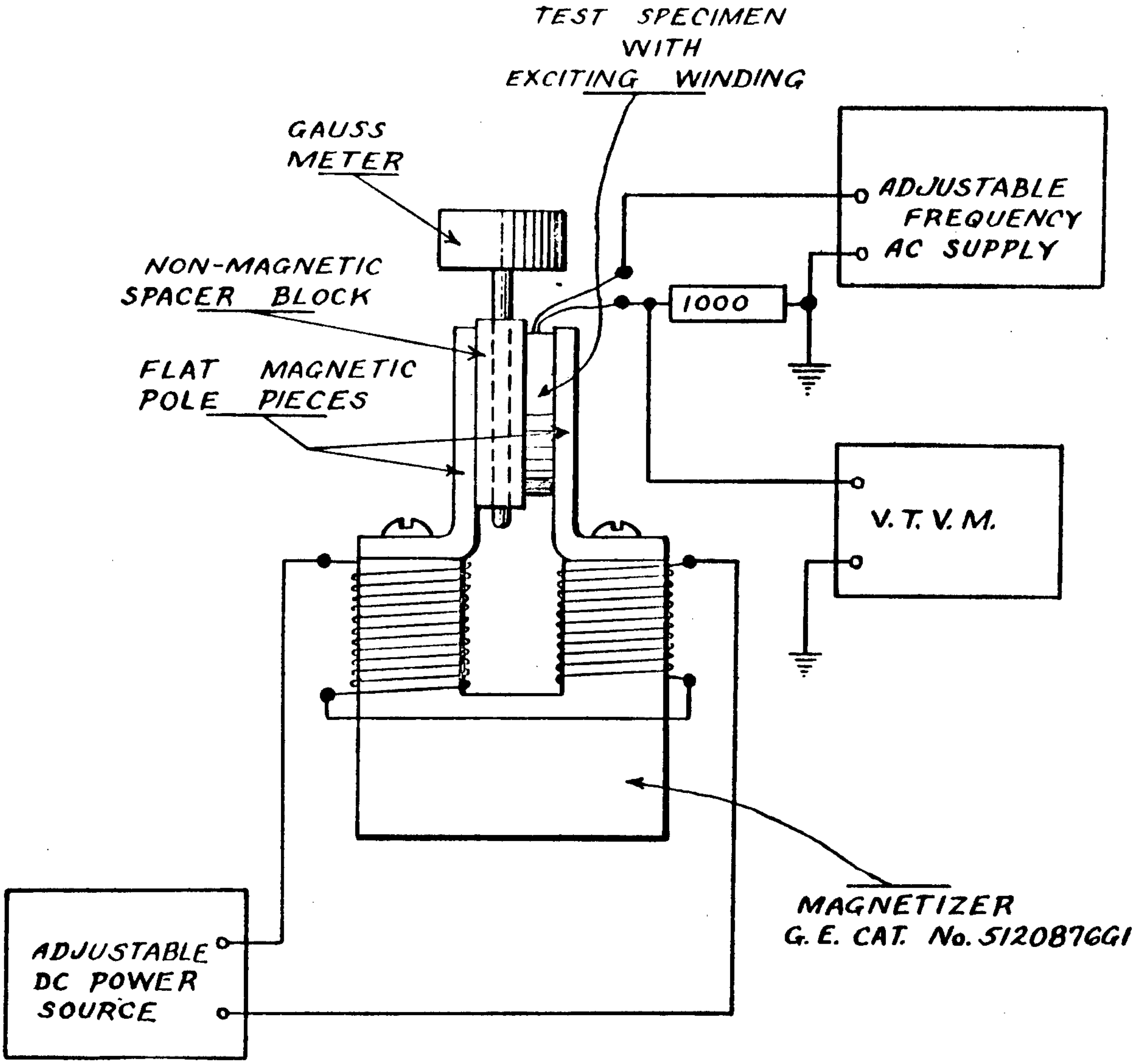
MAGNETIC MEASUREMENTS BY THE VECTOR DIAGRAM METHOD



NOTE: VALUES OF C AND R ARE SELECTED AS REQUIRED FOR SPECIFIC TESTS.

PRACTICAL TEST CIRCUIT
FIGURE 105


TYPICAL VECTOR DIAGRAM
DATA:
TAPE WOUND CORE
SIZE #5340
0.002" SUPERMALLOY
0 DC BIAS
f = 2000 ~
C = 0.0535 MFD.
N_E = 81 TURNS
N_K = 53 TURNS
R = 5.02 OHMS
A = 0.086 cm² ℓ = 5.00 cm
TEST READINGS:
V_i = 9.05 millivolts
V_C = 2.70 Volts
V_S = 2.78 Volts
V_K = 1.6 Volts
V_L = (N_E / N_K)(V_K)
= 2.45 VOLTS
CALCULATIONS AND DETERMINATIONS:
X_C = 1 / 2πfC
= 1 / (6.28)(2000)(0.0535)(10⁻⁶)
= 1490 OHMS
I_AC = V_C / X_C
= 2.70 / 1490
= 1.81 MILLIAMPERES
E_X = 1.02 Volts (from diagram)
E_R = 2.23 Volts (from diagram)
Q = E_X / E_R
= 1.02 / 2.23
= 0.457
MW = (E_R)(I_AC)
= (2.23)(1.81)(10⁻³)
= 4.04 MILLIWATTS
R_E = E_R / I_AC
= 2.23 / 1.81(10⁻³)
= 1230 ohms
B_p = 10⁸ V_L / 4.44(A)(N_E)(f)
= 10⁸(2.45) / 4.44(0.086)(81)(2000)
= 3960 gausses
H_p = 4π N_E I_AC √2 / ℓ
= 4(3.14)(81)(1.81)(10⁻³)(1.414) / 5.00
= 0.052 oersteds
μ_AC = B_p / H_p
= 3960 / 0.052
= 76,000
L = X_L / 2πf
X_L = E_X / I_AC
= 1.02 / 1.81(10⁻³)
= 564 OHMS
L = 564 / (6.28)(2000)
= 0.045 HENRIES
V_S ARC
V_L ARC
A
B
V_L
V_S
V_C
E_X
E_R
I_AC
Volts
3
2.5
2
1.5
1
0.5
0
0.5
1
1.5
2
2.5
3
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
FIGURE 106



TEST SETUP FOR THE DETERMINATION
OF
THE EFFECTS
OF
TRANSVERSE BIAS FIELDS
FIGURE 107

APPENDIX B

A NEW OSCILLATOR

After a large quantity of data on different materials had been secured, it was decided that the design of inductors that could be controlled with a microwatt of control power was not practical for operation over more than a very limited range, if it were necessary for these inductors to be used in oscillator tank circuits. It was found that the Q values of such inductors were quite low. A value as high as five was unusual. The effective resistances of the inductors were found to be in the thousands, or tens of thousands of ohms.

A very serious consideration of this problem finally led to the conception of the idea of using the effective resistances of a pair of the inductors in an R-C tuned oscillator. An R-C tuned oscillator has been used in the General Electric Metals Comparator for several years. It was speculated that it might be possible to adapt the low Q inductors to use in this type of oscillator. The normally variable capacitors would be fixed in value, and the effective resistances of the inductors would be controlled to change frequency.

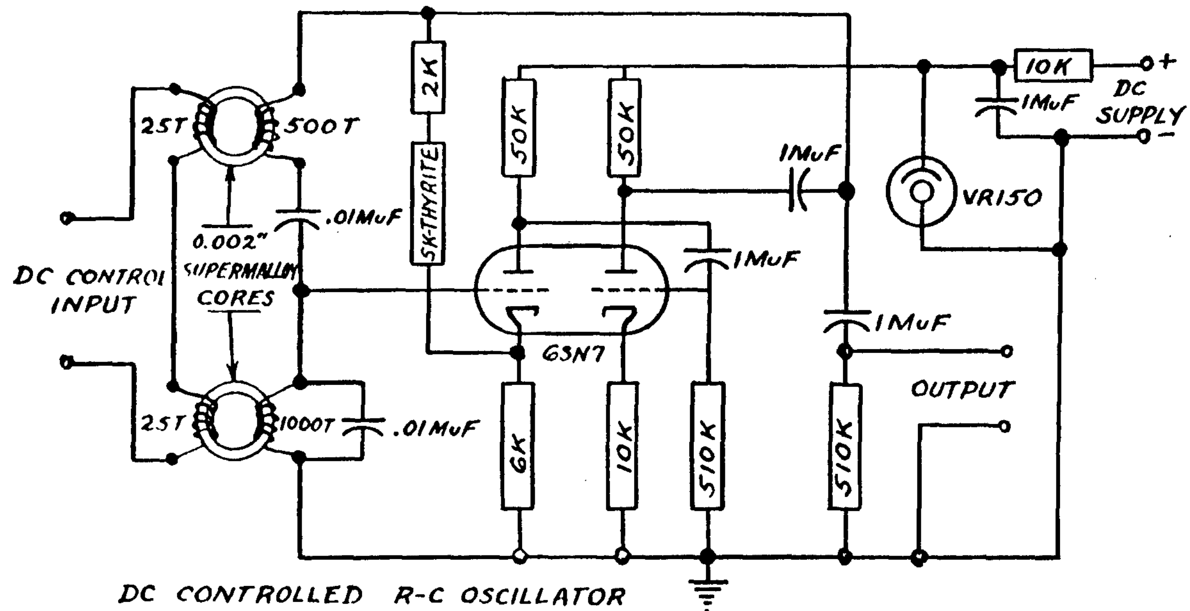
The oscillator shown in Figure 98 was constructed and tested. This oscillator was found to operate successfully. The zero bias frequency of oscillation was about 240 cycles, and with less than a microwatt of control power, this frequency could be increased to about 600 cycles per second. It will be noted at this point that several of the components in this circuit are much larger than necessary for operation, but the main objective at this stage of the investigation was to secure the desired operation.

The two 10 watt lamps in the cathode returns of the 6SN7 tube are used for stabilization of the oscillator. It was decided that stabilization could be secured in a different manner, so the circuit of Figure 98 was modified to that of Figure 108. In this circuit, stabilization is secured by means of a Thyrite resistor, instead of the two lamps. This circuit was also found to operate satisfactorily.

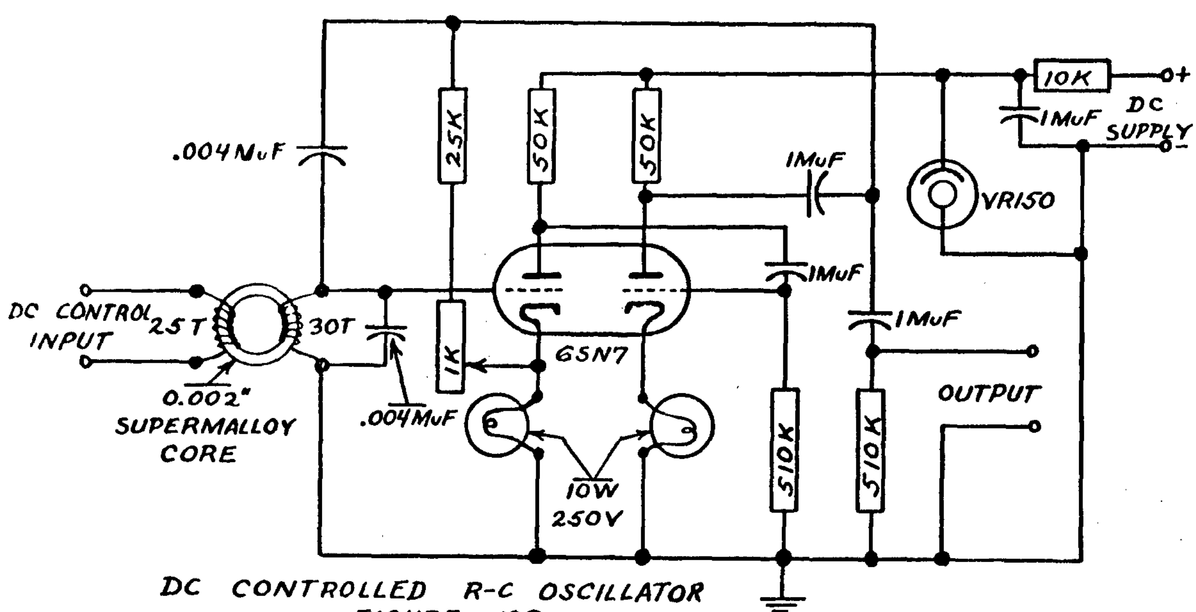
A further modification is shown in Figure 109. In this case, only one inductor was used. This circuit was found to operate in the manner desired.

The last modification is shown in Figure 99. This circuit uses the Thyrite stabilizer, and a single inductor for frequency control. With zero DC control power, oscillation occurred at about 36,000 cycles, and it was increased to about 45,000 cycles with less than a microwatt of control power. By changing capacitors, the oscillation frequencies were increased to about 60,000 cycles. The circuit of Figure 99 can be used with a high impedance control source.

It is believed that transistors could probably be used in place of the vacuum tube, with a further reduction in size, since the battery required for transistor operation would probably be smaller than that required for a vacuum tube.



DC CONTROLLED R-C OSCILLATOR
FIGURE 108



DC CONTROLLED R-C OSCILLATOR
FIGURE 109

APPENDIX C

SUBMINIATURE VARIABLE INDUCTOR DESIGN

The optimum specifications for an inductor to be used in the new oscillator described in Appendix B are not known at the present time. However, it is known that inductors can be designed from the included data that are satisfactory for this oscillator, and it is expected that further investigation with the oscillator will provide more information about the required specifications of such inductors.

The use of the data included in this report in connection with the design of an inductor to a given set of specifications, will be described by using an example calculation.

Assume that the following operating conditions are specified:

1. Frequency of operation, $f=10$ kilocycles.

2. Operating voltage, $V_L=10$ volts, RMS.

3. Effective resistance, $E_R=10{,}000$ ohms.

The design procedure is as follows:

1. A core of 0.002" Supermalloy tape 1/8" wide, strip wound to an inside diameter of 1/2" and an outside diameter of 3/4" will be used. This is the Arnold Engineering Company size #5340. The core weight, G, will be 3.8 grams, the density is 8.77 and the mean length of the magnetic circuit ℓ is five centimeters. These data are catalog information, and can be verified by measuring a core of this material.

2. Calculate the cross sectional area A of the core.

$$A = \frac{(\text{Weight})}{(\text{Density})(\text{length of mag. circuit})} \qquad \mathbf{2.}$$

$$= \frac{G}{8.77\ell}$$

$$= \frac{3.8}{(8.77)(5)}$$

$$= 0.087 \text{ sq. centimeters}$$

3. Assume a peak flux density, B_p, for a tentative calculation.

$$B_p = 2000 \text{ gausses}$$

4. Determine the core loss, MW_G, in milliwatts per gram at this peak flux density and at the specified operating frequency. Use Figure 87.

$$MW_G = 3.85 \text{ milliwatts per gram}$$

5. Calculate total core loss, W_T.

$$W_T = \frac{3.85}{1000}(3.8) \qquad 7.$$

$$= 14.6 \text{ milliwatts}$$

6. Calculate the RMS value of the exciting current, I_{AC}, using the specified value of effective resistance, R_E.

$$I_{AC} = \sqrt{\frac{W_T}{R_E}} \qquad 8.$$

$$= \sqrt{\frac{14.6}{(1000)(10,000)}}$$

$$= 1.21 \text{ milliamperes}$$

7. Determine the peak value of magnetizing force, H_{AC}, required to produce the assumed value of B_p at the specified operating frequency, f.

$$H_{AC} = .075 \text{ oersteds, from Figure 89}$$

8. Calculate the tentative number of turns, N_L, to use for inductor winding.

$$\frac{N_L I_{AC}}{\ell} = 0.795(H_{AC})(0.707) \qquad 9.$$

$$\frac{N_L I_{AC}}{\ell} = 0.795(.075)(.707)$$

$$= .0422 \ \frac{\text{ampere turns}}{\text{cm.}} \text{ (RMS value)}$$

$$N_L = \frac{(0.0422)}{I_{AC}}$$

$$N_L = \frac{0.0422(5)(1000)}{1.21}$$

$$= 175 \text{ turns}$$

9. Calculate the applied voltage, V_L, that would be required to produce the assumed peak flux density, B_p, using N_L turns.

$$V_L = \frac{4.44\ B_p A N_L f}{10^8} \qquad \textit{10.}$$

$$= \frac{4.44(2000)(0.087)(175)(10^4)}{10^8}$$

$$= 13.5 \text{ volts}$$

10. The effective resistance, R_E, is altered most by the incremental permeability (which does not change rapidly with peak flux density) and the number of turns, N_L.

Therefore, assume an operating voltage of 10 volts across N_L and calculate the peak flux density.

$$10 = \frac{4.44(B_p)(0.087)(175)(10^4)}{10^8} \qquad \textit{11.}$$

$$B_p = 1480 \text{ gausses}$$

11. Calculate R_E with same number of turns, but at the specified operating voltage.

$$MW_G = 2.1 \text{ milliwatts per gram}$$

$$W_T = 2.1(3.8) \qquad \textit{12.}$$

$$= 7.98 \text{ milliwatts}$$

$$I_{AC} = \frac{0.795(0.707)(\ell)(H_{AC})}{N_L} \qquad \textit{13.}$$

$$= \frac{(0.795)(0.707)(5.0)(0.058)}{175}$$

$$= 0.933 \text{ milliamperes}$$

$$R_E = \frac{W_T}{I_{AC}^2} \qquad \textit{14.}$$

$$= \frac{7.98(10^6)}{1000(.93)^2}$$

$$= 9{,}240 \text{ ohms}$$

Since this value is less than the specified value of 10,000 ohms, it will be necessary to change N_L.

12. Assume a new value of 185 turns for N_L and repeat the calculation of Steps 10 and 11.

$$B_p = \frac{V_L(10^8)}{4.44\ AN_Lf}$$ 15.

$$= \frac{10(10^8)}{4.44(0.087)(185)(10^4)}$$

$$= 1400 \text{ gausses}$$

$$MW_G = 1.9 \text{ milliwatts per gram}$$

$$W_T = 1.9\ (3.8)$$

$$= 7.23 \text{ milliwatts}$$

$$I_{AC} = \frac{0.795(0.707)(l)H_{AC}}{N_L}$$ 16.

$$= \frac{(0.795)(0.707)(5)(0.056)}{185}$$

$$= 0.85 \text{ milliamperes}$$

$$R_E = \frac{W_T}{I^2_{AC}}$$ 17.

$$= \frac{7.23(10^6)}{(10^3)(.85)^2}$$

$$= 10{,}000 \text{ ohms}$$

This is the specified value, but if the change to 185 turns had not resulted in the correct value of R_E, another change would have been made.

13. Determine the zero bias incremental permeability, μ_i, from Figure 90.

$$\mu_i = 25{,}000$$

14. Calculate the tentative value of the zero bias inductance, L_T, of the winding, N_L.

$$L_T = \frac{1.257\ N_L^2 A\mu_i}{10^8}$$ 18.

$$= \frac{1.257(185)^2(0.087)(25{,}000)}{(10^8)(5)}$$

$$= 0.187 \text{ henries}$$

15. Calculate the value of $\frac{V_L I_{AC}}{W_T}$. This will be used as the value of $\frac{EI}{W}$ in determining the corrected value of inductance, L.

$$\frac{EI}{W} = \frac{V_L I_{AC}}{W_T}$$ 19

$$= \frac{10(0.85)(10^3)}{10^3(7.23)}$$

$$= 1.176$$

16. Determine the correction factor, K, from Figure 96.

$$K = 0.52$$

17. Calculate the corrected value of inductance, L, of the inductor.

$$L = KL_T$$ 20

$$= 0.52\ (0.187)$$

$$= 0.097 \text{ henries}$$

18. Calculate the inductive reactance, X_L, at frequency, f.

$$X_L = 2\pi fL$$ 21

$$X_L = 2(3.14)(10^4)(0.097)$$

$$= 6080 \text{ ohms}$$

19. Calculate the quality factor, Q, of the inductor.

$$Q = \frac{X_L}{R_E}$$ 22

$$= \frac{6080}{10{,}000}$$

$$= 0.608$$

20. The maximum amount of DC control bias that can be secured with one microwatt of control power is approximately 0.05 ampere turns per centimeter, if the total space available for control windings is filled (on this size core). This will vary slightly, depending on the amount of N_L winding used, and the type of insulation. Using a value of 0.05 ampere turns per centimeter as a maximum amount of control, it can be seen from Figure 93 that the incremental permeability at 500 gausses and 10 kilocycles can be expected to be decreased to about 33% of its zero bias value with one microwatt of DC control power. Figure 94 indicates that at the higher peak flux density actually used in the

example, the decrease in incremental permeability would be somewhat less, to about 37% of its zero bias value, but this is ample.

The effective resistance decreases with a decrease in incremental permeability, and usually at a somewhat faster rate, but this is a variable relationship, depending on the particular values of frequency and flux densities that are used. The relationship is complex, and best determined by trial.

The results of the above calculations form a basis to use in formulating the winding specifications.

Since the RMS value of I_{AC} will be less than one milliampere, the wire size will be determined by the mechanical considerations. A convenient size to use is 0.005 inch Heavy Formex insulated copper wire. The DC resistance of the winding is not important. The core loss will be less than 10 milliwatts, so there will be no heating problem.

The winding of 185 turns can be applied directly over the Nylon protective case.

A layer of suitable type insulation should be used to protect the 185 turn winding, and the remaining space should be filled with a control winding of as large size copper wire as is convenient to handle. This may be #18 or #20 Heavy Formex insulated wire.

If more control is secured than is desirable, this should be reduced by using a resistor in series with the control winding. The use of such a resistor will also result in faster response to control.

It is emphasized at this time that the data included in this report are average data, and that since core materials vary, different cores will vary by different amounts from the values given.

The author also wishes to mention the fact that since the American Standard definition of an inductor is, "An inductor is a device, the primary purpose of which is to introduce inductance into an electric circuit," the device herein designed is really a controlled resistor. "A resistor is a device, the primary purpose of which is to introduce resistance into a circuit."